Australian National University

The Ageing Mind of the Double Brain: Studies in Hemispheric Asymmetry for Global-Local Processing

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October 2025

A thesis submitted for the degree of Doctor of Philosophy of
The Australian National University

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Declaration

This thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at The Australian National University. The work presented is original to the best of my knowledge and belief, except where due reference is made. It has not been submitted for any other degree or qualification at this or any other university.

Chapters of this thesis include work that has been published or is in preparation as a manuscript for submission. A full list of these works is provided below.

Published

Chen, H., Cox, J. A., & Aimola Davies, A. M. (2024). Hemispheric asymmetry for global-local processing: Effects of stimulus category and ageing. *Quarterly Journal of Experimental Psychology, 78*(8), 1627-1648. https://doi.org/10.1177/17470218241280800

Chen, H. & Aimola Davies, A. M. (2025). Individual differences in hemispheric asymmetry for global-local processing in young and older adults. *Laterality, 30*(2–6), 136–167. https://doi.org/10.1080/1357650X.2025.2577355

Chen, H. & Aimola Davies, A. M. (2025). Global-local processing and the Ebbinghaus Illusion: Group and individual differences in young and older adults. *Perception*, *55*(4), 384–411. https://doi.org/10.1177/03010066251395949

Manuscript in Preparation

Chen, H., Low, L. T., Laria, N., & Aimola Davies, A. M. (2026). *Orienting of Attention in a Global-Local Processing Task: Effects of Ageing*. (Manuscript in preparation).

Haiwen Chen, October 2025

Acknowledgements

I did not expect the Acknowledgements to be the hardest section of this thesis to write. I feel emotional, grateful, and deeply moved as I put these words together. Looking back at myself four years ago, I could not imagine that my PhD journey would come this far. Both this thesis and I have been carried forward by the people who guided, supported and encouraged me along the way.

First and foremost, I am deeply grateful to my supervisor, Associate Professor Anne Aimola Davies, for her invaluable academic guidance and insight throughout my PhD journey. Her expertise and high standards have challenged me to grow as a researcher and to pursue my work with clarity and rigour. Just as importantly, she has been more than a supervisor: a mentor, a supporter, a role model, and at times a friend. She celebrated my successes with me, and when I struggled, she offered patience, perspective, and the extra push I needed to move forward. For both the academic and personal guidance she has given me, I am sincerely thankful. I would also like to thank my panel member, Dr Jolene Cox, whose insightful comments on my research have been greatly appreciated.

I would also like to express my gratitude to the Australian National University (ANU), where my academic journey began as an undergraduate student and continued through to my PhD. I am grateful for the education and opportunities I have received here, which have shaped both my research and my personal growth. I extend my thanks to all the academics and staff at the School of Medicine and Psychology for their expertise, guidance, and support during my candidature. I am equally thankful to my fellow PhD colleagues for their friendship and for the many conversations that made this journey both intellectually stimulating and personally meaningful. I also thank all the staff and student representatives at the ANU Students' Association (ANUSA) for the opportunity to work with them, which created a welcoming sense of community that I will always value as part of my PhD journey.

I am especially grateful to my friends, who have supported me with kindness, humour, and joy throughout these years. I am also thankful for my feline friends, Freckles (发哥)

and Melas (黑黑), whose fluffy presence and entirely one-directional emotional support accompanied me throughout the PhD journey. It was their reliable morning hungry meows that made sure I never missed a morning, whether I was ready or not.

Last but not least, I would like to express my gratitude to all my family members in China and in Australia. Their unwavering love and support have been a safe harbour where I could pause, recharge, and set sail once more toward both the challenges and the excitement ahead.

Abstract

Global-local processing refers to a visual attentional mechanism that involves directing attention either globally (to an overall visual scene) or locally (to the finer elements within the scene). The two hemispheres of the brain demonstrate functional asymmetry for global-local processing, with global processing specialised in the right hemisphere and local processing specialised in the left hemisphere. Healthy ageing has been shown to influence global-local processing, with evidence suggesting that older adults demonstrate a local-processing bias. The right-hemisphere ageing hypothesis has been put forth to explain this bias, proposing that right-hemisphere functions are more vulnerable to ageing. In this thesis, hemispheric asymmetry for global-local processing was investigated using a hierarchical-figures task, in which a large stimulus was made up of several small stimuli. The hierarchical figures were presented briefly to the left or right visual field, such that information was initially processed by the contralateral hemisphere.

Study 1 (Chapter 2) was an investigation of hemispheric asymmetry for global-local processing in neurologically healthy right-handed young (*N* = 27) and older (*N* = 34) adults. The question addressed was: *Do stimulus categories with different demands on visuospatial-verbal processing (letters, verbalisable objects, and nonverbalisable shapes) influence hemispheric asymmetry for global-local processing in young and older adults?*

Study 2 (Chapter 3) was an investigation of the role of the right hemisphere in the non-directional component of attentional orienting in neurologically healthy right-handed young (*N* = 39) and older (*N* = 38) adults. The question addressed was: *Do older adults demonstrate greater difficulties with disengaging attention from local-level information when correct responding required re-orienting attention to global-level information?*

Study 3 (Chapter 4) was an investigation of individual differences in hemispheric asymmetry for global-local processing in neurologically healthy right-handed young (*N* = 127) and older (*N* = 58) adults. The questions addressed were: *Do individual young and older adults demonstrate right-hemisphere specialisation for global processing and left-*

hemisphere specialisation for local processing. If so, *Do these individual differences in hemispheric asymmetry account for age-related changes in global-local processing*?

Study 4 (Chapter 5) was an investigation of age-group differences and individual differences in the perception of the Ebbinghaus illusion in neurologically healthy young (N = 87) and older (N = 58) adults. The question addressed was: *Does a local-processing bias reduce susceptibility to the Ebbinghaus illusion?*

Four key conclusions emerged from this research. First, healthy ageing influences two aspects of global-local processing. Older adults demonstrate greater difficulties with: (1) processing global-level information, and (2) disengaging attention from local-level information for the purpose of re-orienting attention to global-level information. Second, hemispheric asymmetry for global-local processing remains intact with age. In young and older adults, the right hemisphere (when compared to the left hemisphere), is more efficient for processing global-level information, and the left hemisphere (when compared to the right hemisphere) is more efficient for processing local-level information. Third, evidence for the right-hemisphere ageing hypothesis was mixed. Although older adults do demonstrate age-related difficulties in global processing, the right hemisphere of older participants was still more efficient compared to the left hemisphere at processing global information. Fourth, there are individual differences in the processing of global-level and local-level information.

This thesis provides future research directions for understanding how healthy ageing influences functional hemispheric asymmetry, and the impact this has on visual attention across the life span.

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Chapter 1 The Double Brain Through History

> "*...I reflect that the other parts of our brain are all of them double, just as we have two eyes, two hands, two ears, and finally all the organs of our outside senses are double; and inasmuch as we have but one solitary and simple thought of one particular thing at one and the same moment, it must necessarily be the case that there must somewhere be a place where the two images which come to us by the two eyes, where the two other impressions which proceed from a single object by means of the double organs of the other senses, can unite before arriving at the soul, in order that they may not represent to it two objects instead of one...*"
>
> —Descartes (1649/1975)

1.1 History of Searching for the Seat of the Soul

The human endeavour of searching for the seat of the soul extends across numerous ancient civilisations, with the heart, rather than the brain, predominantly recognised as the locus of the soul. In ancient Egypt, as documented in the Book of the Dead (circa 1600 BCE), the heart was conceptualised as the source of intelligence, character, emotion, and memory, while also serving a crucial role in the afterlife. This philosophical and religious significance was reflected in ancient Egyptian funerary practices, where the heart was preserved within mummified corpses while other organs were extracted. Similarly, ancient Chinese philosophical and medical traditions attributed cognitive significance to the heart. The foundational medical text Huangdi Neijing (literally the Inner Canon of the Yellow Emperor; circa 485–200 BCE) postulated that the heart regulated emotional equilibrium, thereby facilitating perceptual clarity. With a similar conceptualisation, the Confucian philosopher Xunzi (circa 310–238 BCE) proposed that the heart was the foundation of comprehensive understanding, arguing

that it integrates sensory information from different sources, thus enabling accurate visual and auditory perception. Within the Aristotelian philosophy (circa 384–322 BCE), the heart was positioned as the seat of the soul, functioning as the source of spiritual and cognitive processes while anatomically connecting the systems of the body through the blood vessels. In contrast, the brain was conceptualised primarily as a thermoregulatory organ designed to circulate blood flow for cooling the heart (see Brandt & Huppert, 2021; Hansotia, 2003 for reviews).

Understanding the seat of the soul changed over the centuries, gradually shifting from the heart to the brain. The Greek physician Diocles of Carystus (circa 375–295 BCE) proposed that the soul resided in two locations—the heart as the primary seat and the brain as the secondary seat. Remarkably, Diocles may have been among the earliest in history to propose that the two hemispheres of the brain demonstrate specialisation in different cognitive domains (Lokhorst, 1982). Diocles stated that:

> "...there are two brains in the head, one which gives understanding, and another which provides sense perception. That is to say, the one which is lying on the right side is the one that perceives; with the left one, however, we understand" (as cited in Lokhorst, 1982, p. 34).

However, Diocles's theory failed to gain significant traction, as subsequent philosophical and medical thoughts predominantly emphasised either the brain or the heart as the seat of the soul, overshadowing Diocles's insights regarding functional hemispheric asymmetry. The Greek physician Galen (circa 130–200 CE) was among the first to propose a significant association between the brain and the mind. Interestingly, Galen attributed mental functions not to brain tissue, but to the brain ventricles, the fluid-filled cavities of the brain that he believed contained the soul and governed memory, imagination, cognition and language (Brandt & Huppert, 2021).

Centuries later, the French philosopher René Descartes (1596–1650 CE) localised the seat of the soul within the brain's pineal gland, now recognised in contemporary neuroscience as an endocrine structure regulating circadian rhythms. Descartes recognised the bilateral structure of the brain but was concerned with explaining how our mind remains unified. This supposed contradiction between the double brain and a single

mind prompted his philosophical investigation into how the human mind avoids dual perception—specifically, how humans circumvent experiencing two distinct streams of thought and sensory information from the two hemispheres. Descartes proposed the pineal gland as the neuroanatomical site where the two streams from the two hemispheres of the brain unite. Descartes provided three justifications for this proposal: (1) the pineal gland was a singular structure rather than a pair of structures; (2) the pineal gland was located at the centre of the brain; (3) the pineal gland was unique to human neuroanatomy, although this assumption is now known to be incorrect. Notably, while Descartes recognised the bilateral structure of the brain, he did not postulate specific functional differences between the two hemispheres (Harrington, 1987). Although evidence from contemporary neuroscience has refuted Descartes's localisation hypothesis, his inquiry into how the double brain generates a unified mind established a philosophical framework for modern investigations into functional hemispheric asymmetry. This philosophical framework involves understanding how the lateralised processing of information across the two hemispheres contributes to, rather than fragments, our integrated sense of self and cognition.

In the early 19th century, Austrian anatomist Franz Joseph Gall developed phrenology, which arguably represented an extreme extension into the historical search for the seat of the soul. There were three principles in Gall's phrenology: (1) the brain functions as the organ of the mind; (2) distinct brain regions govern specific mental faculties; (3) the relative strength of these mental faculties could be assessed through physical examination of the features in the corresponding regions of the skull, including shape, size, and bumps. For example, phrenologists claimed that individuals with pronounced mirthful dispositions (i.e., those who like to laugh) would display two distinctive frontal bumps compared to their 'dourer' contemporaries (see Spurzheim, 1815; as cited in Parker Jones et al., 2018). Noteworthy in phrenology was the view of the double brain. Gall recognised the bilateral structure of the brain and proposed that the two hemispheres are perfect duplications of each other, both in terms of structural organisation and localisation of mental faculties. Gall found this structural and functional hemispheric duplication convincing as a protective mechanism against injury, reasoning that functions disrupted in one hemisphere could remain intact in the other

hemisphere. Interestingly, phrenologists simultaneously maintained the view that this hemispheric duplication enabled the two hemispheres to operate independently to some extent. Discordant action between the two hemispheres was argued to lead to certain forms of madness and insanity (e.g., delusion caused by unilateral brain injury) (Harrington, 1987).

In the mid-19th century, English physician Arthur Wigan presented a perspective that was distinct from phrenology. While phrenologists focused on the potential consequences of hemispheres operating independently (leading to madness or insanity), Wigan proposed that the two hemispheres naturally operate independently. He argued that each hemisphere possesses its own mind, capable of independent reasoning and perception. However, in normal functioning, one hemisphere typically dominates consciousness, creating our perception of a single, unified self. Wigan's conviction in his theory of mind duality stemmed from his autopsy of a man who, despite having one hemisphere destroyed, maintained the ability to engage in rational conversation and writing. Similar to phrenologists, Wigan attributed mental health disorders to discordant action between the two hemispheres, but through a different mechanism. Wigan argued that mental health disorders arise when one hemisphere becomes diseased, causing a discrepancy between the two minds (Clarke, 1987; Harrington, 1987). Notably, while noting the independent operations of the two hemispheres, Wigan did not address whether the two hemispheres were functionally distinct.

By this point in history, the bilateral structure of the brain was widely recognised, and some consensus had emerged regarding the brain's role as the seat of the soul. However, this understanding was predominantly based on philosophical speculation or pseudoscientific claims, rather than on rigorous scientific evidence. Importantly, hemispheric *symmetry* remained the prevailing view, with this prevailing view assuming that both sides of the brain were identical in their functions. The modern concept of functional hemispheric asymmetry—the idea that the two hemispheres specialise in different cognitive functions—had not yet emerged. It was Paul Broca's groundbreaking work in the mid-19th century that initiated a shift in our understanding of the functional organisation of the two hemispheres.

1.2 Hemispheric Asymmetry Research

Hemispheric asymmetry refers to the concept that the left hemisphere and right hemisphere of the brain are not identical, differing in both their structural organisation (e.g., volume, shape) and functional specialisation. In particular, functional hemispheric asymmetry describes how certain cognitive functions are more dominantly controlled or processed in one hemisphere compared to the other hemisphere. In the literature, the term hemispheric asymmetry is often used interchangeably with related terms such as hemispheric specialisation, cerebral lateralisation, or cerebral asymmetry. This thesis will focus specifically on functional hemispheric asymmetry (hereafter referred to as hemispheric asymmetry).

1.2.1 From Broca's Discovery to Left Hemisphere Superiority

It is widely accepted that our modern understanding of hemispheric asymmetry began in the mid-19th century with the seminal case study by French physician Paul Broca involving his patient Louis Victor Leborgne, who was also known as Tan. At the age of 30, Leborgne experienced a stroke that resulted in a severe speech impairment. He was only able to consistently produce the single syllable "tan". Despite this impairment in speech production, Leborgne retained intact cognitive functioning, including language comprehension and nonverbal communication. Two decades later, following Leborgne's death in 1861, Broca conducted an autopsy and discovered damage in the left frontal lobe, specifically in a region now known as Broca's area, located in the posterior part of the frontal lobe of the left hemisphere. Drawing inspiration from the earlier work of French physician Jean-Baptiste Bouillaud (1825; as cited in Christman, 2024), who had documented over 100 cases linking impairment in speech production to damage in the left frontal lobe, Broca proposed in his influential report (1861; see Berker et al., 1986 for English translation) that speech was localised in "the third left frontal convolution". In the same report, he introduced the term *aphémie*, derived from the Greek word *aphēmia,* meaning "speechlessness", to describe the speech impairment observed. This term was later replaced by the more widely used term aphasia. Today, Broca's concept of *aphémie*

is recognised as Broca's aphasia or motor aphasia, a condition characterised by impaired speech production while verbal comprehension remains intact.

Around the same time as Broca, in the late 19th century, German physician Carl Wernicke documented a case in which the patient produced fluent, grammatically correct speech that was largely meaningless and accompanied by an impairment to follow verbal commands. Following the patient's death, Wernicke conducted an autopsy and identified damage in the superior posterior region of the left temporal lobe, a region now known as Wernicke's area, located in the posterior superior temporal gyrus of the left hemisphere. In his seminal book (1874), Wernicke proposed that this region was associated with a distinct type of aphasia, termed Wernicke's aphasia or sensory aphasia. Unlike Broca's aphasia, Wernicke's aphasia is characterised by impaired verbal comprehension alongside fluent but nonsensical speech. The discoveries of Broca and Wernicke had two significant implications for later research in neuropsychology, cognitive psychology, and cognitive neuroscience. First, their findings provided strong evidence that the left hemisphere is specialised for language functions, establishing the foundational idea that the two cerebral hemispheres are functionally distinct. Second, their findings introduced the notion that language is not a unitary function but comprises separate cognitive components, speech production and verbal comprehension, each localised in different areas of the left hemisphere, forming a classic example of double dissociation.

By the late 19th century, the concept of functional hemispheric asymmetry had become widely accepted. However, the idea of left hemisphere functional specialisation gradually expanded beyond language functions to include other aspects of cognition, particularly for 'higher-level' functions such as intelligence and reasoning. This led to the prevailing belief that the left hemisphere was the 'superior' or 'dominant' hemisphere, while the right hemisphere was considered the 'subordinate' or 'minor' hemisphere. Essentially, the right hemisphere was considered a weaker version of the left hemisphere, lacking distinctive functional specialisation (see Benton, 1972 for a review). British neurologist John Hughlings Jackson was among the first to challenge this belief of left hemisphere superiority. Jackson (1875) reported a case study of a patient with a

tumour in the temporo-occipital region of the right hemisphere. The patient demonstrated hemiplegia (i.e., paralysis of one side of the body) in her left arm, along with impairments in visual orientation and face recognition, suggesting that the right hemisphere is involved in the processing of visuospatial and face information. Independently, French neurologist Joseph Babinski (1914) described several patients who, following right hemisphere damage, demonstrated hemiplegia on the left side of the body but lacked awareness of their paralysis. *Babinski* termed this condition anosognosia, from the Greek *a* (lack), *nosos* (illness), and *gnosis* (knowledge). Together, the findings of Jackson and Babinski challenged the predominant belief of left hemisphere superiority, providing early evidence that the right hemisphere plays an important role in visuospatial processing, face recognition, and body awareness.

A major turning point in the research of hemispheric asymmetry occurred in the 1960s, with an increase in empirical evidence that has since shaped the theoretical and methodological framework of current knowledge in this area. As outlined by Christman (2024), this growth was driven by the development of two independent behavioural paradigms, the dichotic listening task and the divided visual field design, both of which enabled non-invasive experimental investigation of functional differences between the left hemisphere and right hemisphere.

1.2.2 Dichotic Listening Task

The dichotic listening task involves the simultaneous presentation of two different auditory stimuli, with one auditory stimulus presented to the right ear and the other presented to the left ear. The logic behind the dichotic listening task is based on the contralateral organisation of auditory processing pathways. Auditory input from one ear primarily crosses the midline of the body at the brainstem, transmitting to the contralateral hemisphere. Therefore, auditory stimuli presented to the left ear are first processed by the right hemisphere, and auditory stimuli presented to the right ear are first processed by the left hemisphere. Therefore, hemispheric specialisation for a specific cognitive function can be inferred by performance (e.g., reaction time or accuracy) differences in detecting the corresponding type of auditory stimuli presented to the left

ear compared to those presented to the right ear. Right hemisphere specialisation is indicated by better performance in detecting auditory stimuli presented to the left ear compared to the right ear. Left hemisphere specialisation is indicated by better performance in detecting auditory stimuli presented to the right ear compared to the left ear.

The dichotic listening task was first developed by Broadbent (1956) to examine memory span. It was later adapted by Doreen Kimura (1961a) to study cognitive deficits in two groups of patients: those with unilateral damage to the left temporal lobe and those with unilateral damage to the right temporal lobe. In Kimura's study, a total of six auditory digits were presented in each trial, with half of the digits presented to the left ear and the other half to the right ear. Participants were instructed to report verbally all the digits they heard, regardless of the order of recall. Kimura reported two key findings. First, patients with damage to the left temporal lobe correctly reported fewer digits compared to patients with damage to the right temporal lobe. This overall worse performance in the patients with damage to the left temporal lobe was observed regardless of whether the auditory digits were presented to the left ear or to the right ear. Second, across both groups of patients with unilateral damage to either the left or to the right temporal lobes, the number of correctly reported digits was fewer when the auditory stimuli were presented to the left ear (processed first by the right hemisphere) compared to the right ear (processed first by the left hemisphere), indicating a right ear advantage in recalling auditory digits. Kimura concluded that both findings supported the notion that the left hemisphere is specialised for processing verbal information.

Building on her earlier findings (Kimura, 1961a), Kimura further proposed that the right ear advantage in recalling auditory digits could be extended from clinical patients to a non-clinical population. In a subsequent study, Kimura (1961b) tested the same experiment paradigm with a small sample of 13 right-handed healthy participants. Consistent with her findings in patients with unilateral brain damage, Kimura's findings with healthy participants also demonstrated that there were fewer correctly reported digits when the auditory stimuli were presented to the left ear (processed first by the right hemisphere) compared to the right ear (processed first by the left hemisphere). Later,

Kimura (1963) suggested that, to observe hemispheric asymmetry using the dichotic listening task, it is necessary to present different auditory stimuli simultaneously to both ears, rather than presenting auditory stimuli to one ear at a time. Simultaneous bilateral presentation creates competition between the ipsilateral and contralateral auditory pathways, allowing the dominant hemisphere to process its specialised type of auditory stimuli more efficiently than the non-dominant hemisphere, thus revealing hemispheric asymmetry.

1.2.3 Divided Visual Field Design

In this thesis, hemispheric asymmetry was examined in the context of the visual attentional mechanism of global-local processing. Accordingly, the divided visual field design was the primary behavioural paradigm adopted in this thesis. Unlike the dichotic listening task, which examines hemispheric asymmetry for auditory stimuli, the divided visual field design examines hemispheric asymmetry for visual stimuli.

The divided visual field design involves the presentation of visual stimuli to the left side of central fixation (i.e., in the left visual field; LVF) and/or to the right side of central fixation (i.e., in the right visual field; RVF). There are two major types of stimulus presentation methods in the literature: unilateral stimulus presentation and bilateral stimulus presentation. For the unilateral stimulus presentation, one visual stimulus is presented unilaterally to either the LVF or to the RVF (e.g., Chen et al., 2024; Martin, 1979; Yovel et al., 2001). For the bilateral stimulus presentation, two different visual stimuli are presented simultaneously, with one stimulus presented to the LVF and the other to the RVF (e.g., Boles, 1987, 1990; Brederoo et al., 2017). Similar to the dichotic listening task, the logic behind the divided visual field design is based on the contralateral organisation of visual processing pathways. Visual stimuli presented to one visual field primarily cross the midline of the body at the optic chiasm, transmitting to the contralateral hemisphere (Beaumont, 1982; Bourne, 2006). Therefore, visual stimuli briefly presented to the LVF are first processed by the right hemisphere (RH), and visual stimuli briefly presented to the RVF are first processed by the left hemisphere (LH). Hemispheric specialisation for a specific cognitive function can be inferred by performance (e.g., reaction time or

accuracy) differences in detecting the corresponding type of visual stimuli presented to the LVF compared to those presented to the RVF. Better performance (i.e., faster reaction time or higher accuracy) in detecting visual stimuli presented to the LVF compared to the RVF indicates RH specialisation. Conversely, better performance (i.e., faster reaction time or higher accuracy) in detecting visual stimuli presented to the RVF compared to the LVF indicates LH specialisation.

The development of the divided visual field design was closely related to the research on split-brain patients conducted during the 1960s. The split-brain procedure involves the surgical sectioning of the corpus callosum and other commissures, typically performed to relieve symptoms of epilepsy. As a result of this procedure, direct interhemispheric communication between the two hemispheres is disrupted, allowing researchers to examine cognitive processing within one hemisphere while isolating the interference from the other hemisphere. The split-brain case study by Gazzaniga, Sperry, and Bogen (1962) is widely regarded as having established the methodological foundations of the modern divided visual field design. Beaumont (1982) further commented that it was probably Gazzaniga who should be credited with the development of the divided visual field design.

In the study by Gazzaniga et al. (1962), visual stimuli were briefly presented for 10 ms or 50 ms, to either the LVF or to the RVF, using a tachistoscope, a device designed to present visual stimuli for a very short duration. The researchers reported that the split-brain patient, W. J., demonstrated no impairment in responding to visual stimuli presented to the RVF (processed by the LH), but demonstrated significant 'agnosia' for visual stimuli presented to the LVF (processed by the RH). Importantly, when simple geometric designs, single large numbers, or letters were briefly presented to the LVF (processed by the RH), the patient performed above chance level in retrieving the corresponding visual stimuli from a set of cards using the left hand (controlled by the RH), but not when using the right hand (controlled by the LH). Gazzaniga et al. suggested that these findings indicated that, due to the disconnection between the two hemispheres, the LH was unaware of the visual stimuli that had been processed by the RH from input

presented to the LVF. As a result, the LH was unable to identify correctly the visual stimuli by selecting from the cards using the right hand.

It should be noted that the experiment paradigm of presenting visual stimuli using the divided visual field design had been employed in non-clinical populations several decades before the study by Gazzaniga et al. (1962). However, earlier studies did not interpret performance differences between the two visual fields in terms of hemispheric asymmetry (e.g., Heron, 1957; Mishkin & Forgays, 1952; Orbach, 1952, as cited in Beaumont, 1982), but rather interpreted performance differences between the two visual fields as resulting from the influence of reading direction on attentional allocation toward one visual field over the other visual field. For example, in the study by Mishkin and Forgays, English words or Yiddish words were briefly presented to the LVF or to the RVF. English-Yiddish bilingual participants demonstrated better recognition of English words when presented to the RVF compared to the LVF. Conversely, recognition of Yiddish words was slightly better when presented to the LVF compared to the RVF, although this difference was not statistically significant. Mishkin and Forgays attributed these visual field differences to the reading direction of the two languages. English is read from left to right, so when an English word is presented to the RVF, its initial letters are positioned closer to the right of the central fixation and thus have better visual acuity. Conversely, Yiddish is read from right to left, so when a Yiddish word is presented to the LVF, its initial letters are positioned closer to the left of the central fixation and thus have better visual acuity. However, Mishkin and Forgays also argued that because the English-Yiddish bilingual participants they recruited were more proficient in English than in Yiddish, this may have contributed to the weaker effect for a RVF advantage in Yiddish word recognition.

Christman (2024) suggested that Bryden (1966) was among the earliest to argue that visual field differences in verbal recognition tasks in non-clinical populations reflected hemispheric asymmetry for verbal processing rather than reading direction. In Bryden's study, normally-oriented verbal stimuli and mirror-imaged verbal stimuli, both consisting of either a single letter or a string of three letters, were briefly presented to the LVF or to the RVF. Bryden argued that the reading direction for normally-oriented verbal

stimuli is from left to right, whereas the reading direction for mirror-imaged verbal stimuli is from right to left. Therefore, if reading direction was the major factor driving the visual field differences observed previously, there should be a RVF advantage for the recognition of normally-oriented verbal stimuli (as the initial letters are positioned closer to the right of central fixation) and a LVF advantage for the recognition of mirror-imaged verbal stimuli (as the initial letters are positioned closer to the left of central fixation). However, the results indicated that recognition of verbal stimuli was better when presented to the RVF compared to the LVF, regardless of whether it was the normally-oriented verbal stimuli or the mirror-imaged verbal stimuli. Bryden concluded that this overall RVF advantage for verbal recognition tasks likely reflects LH specialisation for verbal processing, given that stimuli presented to the RVF are first processed by the LH.

The surge of research using the divided visual field design with non-clinical populations did not occur until the 1970s, accompanied by growing confidence in applying a neuropsychological interpretation to the findings for visual field differences in the context of hemispheric asymmetry. This shift was partially driven by advances in the understanding of the mechanisms and methodological considerations underlying the divided visual field design.

1.2.4 From the Dichotomous Approach to the Componential Approach

Much of the hemispheric asymmetry research conducted in the late 1960s and 1970s was driven by the goal to identify ultimate functional dichotomies between the two hemispheres (Christman, 2024). Specifically, the assumption was that all cognitive components could be classified into a single overarching pair of opposing categories, such that one hemisphere was thought to specialise in processing all stimuli and tasks belonging to one category, while the other hemisphere specialised in those belonging to the opposite category. This dichotomous approach was characterised by two key features. First, it did not consider how the two hemispheres might cooperate in processing the same task or stimuli; instead, it focused on the absolute advantage of one hemisphere over the other for a given type of task or stimulus (Christman, 2024). Second, it relied on a reductionist assumption that a single, one-for-all dichotomy (e.g.,

visuospatial *versus* verbal processing) could account for all cognitive functions, such that every function attributed to the RH was categorised under one category of the dichotomy (e.g., the category of visuospatial processing), and every function attributed to the LH was categorised under the other category of the dichotomy (e.g., the category of verbal processing) (Hellige, 1993).

The most prominent dichotomy proposed during this era was the distinction between visuospatial processing and verbal processing, with the proposal that the RH is specialised for all visuospatial tasks and the LH is specialised for all verbal tasks. This dichotomy emerged naturally, as accumulating neuropsychological evidence indicated that impairments in visuospatial processing were associated with damage to the RH (e.g., Jackson, 1875; Paterson & Zangwill, 1944; Warrington & James, 1967). Correspondingly, LH specialisation for language had already been confirmed through the work of Broca (1861) and Wernicke (1874).

The study by Geffen et al. (1972) is an example of the dichotomous approach to the investigation of hemispheric asymmetry for the dichotomy of visuospatial processing *versus* verbal processing. Geffen et al. adopted a divided visual field design, presenting pairs of letters unilaterally to either the LVF or to the RVF, with each letter appearing in either uppercase or lowercase. There were two different tasks. The first was a name-matching task, in which participants were required to decide whether the two letters presented had the same or different graphemic representation (e.g., “A” and “a” sounded identical). This task was interpreted by the researchers as an index of verbal processing. The second was a physical-matching task, in which participants were required to decide whether the two letters presented were physically identical (e.g., “A” and “A” were physically identical, but “A” and “a” were not physically identical). This task was interpreted as an index of visuospatial processing, although the use of verbal stimuli (i.e., letters) in Geffen et al.’s study may not have clearly separated verbal processing from visuospatial processing. Nevertheless, Geffen et al. reported better performance on the name-matching task when stimuli were presented to the RVF compared to the LVF, which was interpreted to mean there was LH specialisation for verbal processing. In contrast, better performance on the physical-matching task was observed when stimuli were

presented to the LVF compared to the RVF, which was interpreted to mean there was RH specialisation for visuospatial processing.

The dichotomy between visuospatial processing and verbal processing has been criticised for oversimplifying the functional specialisation of the two hemispheres. One major criticism concerns the ambiguity of the stimulus properties. Verbal stimuli, such as printed letters or words, can be treated either as linguistic materials, containing phonological or semantic information, or as visuospatial patterns based on luminance distribution across space (Hellige, 1993). This criticism is exemplified by the stimulus design used in the study by Geffen et al. (1972) introduced above, where the verbal stimuli (i.e., pairs of letters) could serve as measures either for verbal processing or for visuospatial processing, depending on the specific task instructions. Accumulating evidence revealed that the division of RH specialisation for visuospatial processing and LH specialisation for verbal processing is not absolute. Specifically, the RH plays an important role in verbal processing, in aspects of lexical information (see Bradshaw, 1980; Bradshaw & Nettleton, 1981 for reviews), and the LH is important for certain aspects of visuospatial processing, such as the processing of local features of spatial information (Bradshaw et al., 1976; Mehta et al., 1987) and the perception of temporal order (Efron, 1990).

The limitations of the visuospatial processing and verbal processing dichotomy in explaining hemispheric asymmetry led to the development of alternative dichotomies, with the aim of accounting for an even broader range of cognitive components. One of the most prominent alternatives proposed was the dichotomy between holistic processing and analytical processing. Specifically, it was proposed that the RH is specialised for holistic processing, including the processing of information that is "parallel, diffuse, similarity-detecting, time-independent, spatial, global, synthetic, or Gestalt", whereas the LH is specialised for analytical processing, including the processing of information that is "serial, focal, difference-detecting, time-dependent, [or] sequential" (Bradshaw & Nettleton, 1981; p. 62).

However, two key limitations have been identified for the holistic processing and analytical processing dichotomy: (1) inadequacy in definition and operationalisation, and

(2) a tendency to serve as a post hoc interpretation (Christman, 2024). For instance, within the same type of stimulus, categorisation as either holistic processing or analytical processing can vary depending on the task instructions or design. For face stimuli, tasks that require participants to compare whether two faces differ across multiple features were interpreted as measures of holistic processing. In contrast, tasks that require participants to compare two faces differing on a single feature were interpreted as measures of analytical processing (see Patterson & Bradshaw, 1975). However, the task design used by Patterson and Bradshaw did not clearly specify how many features must be compared to engage holistic processing. Similarly, for verbal stimuli, when verbal stimuli consist of "high-frequency, concrete or imageable" words, the task is considered to involve holistic processing; whereas, when verbal stimuli consist of "low-frequency, abstract or nonimageable" words, the task is considered to involve analytical processing (see Bradshaw, 1980; p. 182). Again, there was a lack of clear operationalisation in distinguishing high-frequency words from low-frequency words. Another example can be found in the study by Nebes (1971). In this study, split-brain patients were shown an arc segment of a circle and were asked to select, from a series of circles, which circle was the one from which the arc segment belonged. The split-brain patients used either their left hand or their right hand for this selection task, and performance was reported to be better when the left hand was used compared to when the right hand was used, indicating a RH advantage. Bradshaw and Nettleton (1981) interpreted these findings as evidence that the task involved holistic processing based on the observed RH advantage. However, as Christman commented, "we do not really know how people perform this task. Perhaps they do it holistically…though it is also possible that they used an analytic strategy, analysing each of [the] whole circles into arc segments and then comparing those to the original stimulus" (p. 192).

By the 1980s, it was recognised that no single, one-for-all dichotomy could fully account for all aspects of hemispheric asymmetry. Accumulating evidence indicated that different cognitive components demonstrated different directions and magnitudes of hemispheric asymmetry (e.g., Allen, 1983; Hellige, 1980). As a result, research on functional hemispheric asymmetry shifted toward a more nuanced, componential approach. There are three key features of this new approach (Christman, 2024; Hellige,

1993). First, the componential approach focused on how the two hemispheres process different cognitive components, rather than seeking a single overarching dichotomy to categorise all cognitive components. Second, the componential approach emphasised how cooperation between the two hemispheres contributes to the performance of an overall task. Third, the componential approach recognised that hemispheric asymmetry is not absolute; instead, both hemispheres are involved in processing all types of information, but they differ in their efficiency for specific types of processing. A more detailed review regarding the absolute model *versus* the relative model of hemispheric asymmetry will be presented later in this chapter (see Section 1.3.4).

Researchers adopting the componential approach have found hemispheric asymmetry across different cognitive processes, including perception, visual attention, language, memory, and emotion. Findings from this research indicate that hemispheric asymmetry for visuospatial processing and verbal processing is far more complex than the simple division proposed by the dichotomous approach, which assumed exclusive RH specialisation for visuospatial processing only and exclusive LH specialisation for verbal processing only. For example, for visuospatial processing, hemispheric asymmetry has been observed for spatial frequency processing, with the RH more efficient in processing low spatial frequency information and the LH more efficient in processing high spatial frequency information (Sergent, 1982; Sergent & Hellige, 1986). Similarly, for verbal processing, hemispheric asymmetry has been observed for lexical processing, with the RH more efficient in processing orthographic relationships, and the LH more efficient in processing phonological relationships (Chiarello, 1985).

While it is beyond the scope of this thesis to review all the divisions identified in the componential approach (see Christman, 2024; Hellige, 1993 for reviews), this thesis will focus specifically on hemispheric asymmetry in the visual attentional component of global-local processing. Global-local processing refers to the allocation of visual attention to either the overall structure of a scene (i.e., global level) or to its finer elements (i.e., local level). Our visual environment is inherently hierarchical; for example, a landscape of trees can be perceived as an entire forest (i.e., global level) or as individual trees in the forest (i.e., local level). To navigate such complex visual environments, the

visual system relies on visual attentional mechanisms that selectively process relevant information (Carrasco, 2011), with global-local processing representing one such mechanism. Research on hemispheric asymmetry for global-local processing was originally influenced by the holistic processing *versus* analytical processing dichotomy. However, it differs from that earlier dichotomy approach in two important ways. First, research on hemispheric asymmetry for global-local processing focuses on how the two hemispheres differ in the deployment of one aspect of visual attention, rather than addressing whether all RH functions can be categorised under the category of global processing and whether all LH functions can be categorised under the category of local processing. Second, research on hemispheric asymmetry for global-local processing adopted a more precise operationalisation than earlier research on the holistic processing and analytical processing dichotomy. This was accomplished most successfully through the use of Navon's (1977) hierarchical figures, which consist of large global stimuli composed of multiple smaller local stimuli. For example, a large global letter 'U' may be constructed from several smaller local 'T' letters. This design allows researchers to measure participants' performance at the global level and at the local level using the same stimulus. A more detailed review of the research on hemispheric asymmetry for global-local processing will be presented in Chapter 2.

1.3 Four Key Aspects of Hemispheric Asymmetry

In the previous sections of this chapter, I reviewed historical perspectives concerning the seat of the soul, tracing the shift in perspective from the heart to the brain, and the early view that the two hemispheres were functionally identical. I also reviewed the historical development of hemispheric asymmetry research, from early clinical case studies to contemporary experimental approaches. This historical review provided the background for understanding how hemispheric asymmetry was first conceptualised and empirically investigated. Building on this background, this section will address four key aspects of hemispheric asymmetry: (1) Why does the human brain demonstrate hemispheric asymmetry? (2) Does hemispheric asymmetry change across the lifespan? (3) Does hemispheric asymmetry vary across individuals? and (4) What are the theoretical interpretations of these hemispheric asymmetry findings?

1.3.1 Why does the Human Brain Demonstrate Hemispheric Asymmetry?

Modern humans belong to the phylum *Bilateria*, which is characterised by a body plan with left-right bilateral symmetry. A compelling evolutionary hypothesis for this symmetry is that it developed as an adaptation to facilitate locomotion—the ability to move from one place to another (Corballis, 2009, 2019, 2021). The body plan of *Bilateria* is organised along three major axes, which evolved in sequence: the antero-posterior axis, the dorsal-ventral axis, and the left-right axis. The antero-posterior axis refers to the head-tail organisation of the body, with a distinct anterior end (head) and posterior end (tail). This axis emerged in response to the need for moving in a straight line (e.g., running, swimming, or flying), which favoured the evolutionary development of forward-facing sensory systems. Sensory organs, such as the eyes, ears, and mouth, evolved at the anterior end (head) to detect stimuli encountered while moving forward. The dorsal-ventral axis distinguishes the dorsal (back) and ventral (front or belly) sides of the body and evolved later as an adaptation to gravity during locomotion. The left-right axis emerged last and enabled the development of paired, symmetrical limbs such as legs, wings, or flippers, which help maintain balance and coordination when moving in a straight line. Sensory systems (e.g., eyes, ears, and mouth) became symmetrically distributed, allowing animals to detect and respond to stimuli from both sides of the body. There was less evolutionary pressure to maintain symmetry in functions unrelated to locomotion. In such cases, asymmetry may have emerged because it offered a selective evolutionary advantage (Corballis, 2019). In other words, both symmetry and asymmetry are shaped by evolutionary adaptation. The development of asymmetry is thought to follow a snowballing process: once asymmetry arises in certain structural and functional mechanisms, environmental pressures may favour those adaptations, increasing their likelihood of being preserved. Over time, these initial asymmetries can become more pronounced, reinforcing a trajectory toward greater asymmetry where it is functionally advantageous (Hellige, 1993).

On the structural level, one of the most obvious examples of asymmetry is the asymmetrical placement of internal organs. This arrangement is thought to provide an adaptive advantage by allowing more efficient use of cavity space (Corballis, 2021). On

the behavioural level, handedness is one prominent example of asymmetry. To be clear, although symmetrical pairs of limbs evolved to support behaviours for reacting to the environment, such as locomotion involving running, swimming, and flying, asymmetry is favoured in behaviours that involve operating on the environment, such as the preferential use of one hand or limb for specific tasks (Corballis, 2009). There is strong evidence for handedness both at the individual and population levels across species. In humans, handedness is clearly evident at the population level, with approximately 90% of individuals being right-handed (Corballis et al., 2012). Some non-human primates also demonstrate population-level handedness (Hopkins, 1996; Hopkins et al., 2004; also see Ströckens et al., 2013 for a review). Similarly, lateralised motor preferences have been observed in other species, including parrots and kangaroos, which show consistent foot or forelimb preferences when feeding or picking up objects (Giljov et al., 2015; Rogers, 1980; as cited in Corballis, 2019).

On the functional level, it is believed that hemispheric asymmetry evolved due to several adaptive advantages. First, neural resources in the brain are limited. As such, it is more efficient for certain functions to be lateralised rather than duplicated across both hemispheres, allowing for better allocation of neural resources to different cognitive functions (Esteves et al., 2020; Hellige, 1993; Vallortigara et al., 2011). Second, duplicating the same function in both hemispheres would require constant interhemispheric communication, which is not time-efficient (Ringo et al., 1994) and may lead to conflicts between competing neural processes (Bisazza et al., 1998; Esteves et al., 2020; Hellige, 1993). Specialising a function within one hemisphere enables faster and more accurate recruitment of neural circuits, allowing for the efficient processing of complex functions such as language. Third, in survival scenarios, different aspects of the same information may be crucial for survival—for instance, the global aspect and the local aspect of a visual scene. It is hard to recruit neural circuits of the same area to process these aspects of information efficiently at the same time. As such, there was evolutionary pressure for the two hemispheres to process the global aspect and the local aspect in parallel (Hellige, 1993).

1.3.2 Does Hemispheric Asymmetry Change Across the Lifespan?

1.3.2.1 Early Development. It is believed that the two hemispheres follow different developmental trajectories on both the structural level and the functional level. During early development, one prominent proposal is that specific regions of the RH mature earlier than their counterparts in the LH. On the structural level, it has been reported that during the prenatal stage, cortical markings and folds surrounding the Sylvian fissure appear earlier in the RH than in the LH (Chi et al., 1977). During primary gyrogenesis, the superior temporal sulcus undergoes cortical folding earlier and displays greater gyral complexity in the RH than in the LH (e.g., Dubois et al., 2007; Habas et al., 2012). On the functional level, it has been widely reported that, across developmental stages from foetus to neonate and preterm infants, the RH demonstrates earlier functional specialisation compared to the LH. This includes preferential responses to sensory stimulation, non-linguistic auditory input, and greater endogenous activity during resting-state conditions (see Bisiacchi & Cainelli, 2022 for a scoping review).

One major account explains how differences in the developmental course of structures between the two hemispheres give rise to functional hemispheric asymmetry. This account concerns the survival-related prioritisation of information processing in the more rapidly developing RH, relative to the LH. For instance, global processing is considered to be of survival importance for visual perception in newborns, as the early visual sensory system is not fully developed at birth and transmits degraded, low spatial frequency visual input (i.e., global, 'blurry' information) to the brain. Because certain structures in the RH develop earlier than those in the LH, the neural mechanisms of the cerebral cortex prioritise processing this low spatial frequency visual input in the RH. As a result, the RH becomes more specialised in the processing of global information (Hellige, 1993).

Later, as the structures of both the visual system and the LH continue to mature, high spatial frequency visual input (i.e., local, 'fine-detailed' information) becomes increasingly available alongside low spatial frequency visual input. The question then arises: why does the LH become specialised for processing the high spatial frequency visual input (i.e., local processing)? One explanation proposed by Turkewitz (1988) is that

the RH is already engaged in processing low spatial frequency visual input (i.e., global information) and is therefore less available to process the new high spatial frequency visual input (i.e., local information). Consequently, the processing of high spatial frequency visual input is allocated to the LH, leading to its specialisation for local processing. A similar logic may apply to other functions that are crucial for survival in newborns and show RH specialisation, such as face recognition, emotion processing, and para-verbal auditory stimuli (e.g., prosody and affective tone in spoken language) (Bisiacchi & Cainelli, 2022).

This account is also consistent with the right-hemisphere conservatism theory proposed by Geschwind and Galaburda (1987; see McManus & Bryden, 1991). This theory proposes that prenatal hormonal influences, particularly testosterone, delay the development of the LH relative to the RH. Because the RH matures earlier, it is less responsive to external stimulation compared to the LH. Dubois et al. (2007) further argued that the delayed maturation of the LH indicates that the LH is less influenced by genetic control, resulting in greater plasticity and thus being more responsive to environmental stimulation, such as language exposure and motor development.

1.3.2.2 Healthy Older Adults. Ageing is related to changes across many aspects of cognitive functioning, including hemispheric asymmetry. Two major theoretical accounts have been proposed to describe how hemispheric asymmetry changes with age: (1) the right-hemisphere ageing hypothesis, and (2) the hemispheric asymmetry reduction in older adults (HAROLD) model.

The Right-Hemisphere Ageing Hypothesis. The right-hemisphere ageing hypothesis proposes that the RH is more vulnerable to ageing than the LH, with LH functions remaining relatively stable across the lifespan. This hypothesis originated from two lines of theoretical speculation. First, as discussed in the previous section (see Section 1.3.2.1), it has been suggested that the two hemispheres follow different developmental trajectories in early life, with the RH maturing earlier than the LH. This observation led to the speculation that the two hemispheres may also diverge in their ageing trajectories, with the RH being more vulnerable to ageing than the LH (Hellige, 1993). Second, as mentioned in the historical development of hemispheric asymmetry

research (see Section 1.2.1), there was a long-standing belief dating back to the late 19th century that the RH was the 'subordinate' or 'minor' hemisphere compared to the LH. At that time, the LH was viewed as specialised for higher-level functions such as language, while the RH was thought to lack distinct functional specialisation. The belief that there was left hemisphere superiority continued to influence hemispheric asymmetry research into the 1960s and 1970s, further leading to the speculation that the RH might not only be functionally weaker but also more vulnerable to age-related changes.

Klisz (1978) was likely the first to propose the right-hemisphere ageing hypothesis, drawing on evidence from performance patterns on the Wechsler Adult Intelligence Scale (WAIS). During the 1960s and 1970s, it was widely believed that subtests from the WAIS and other intelligence tests could be categorised as either RH tasks or LH tasks. Specifically, scores on the WAIS Performance IQ were interpreted as indicative of RH functioning, while scores on the WAIS Verbal IQ were interpreted as indicative of LH functioning (e.g., Reitan & Fitzhugh, 1971). Klisz reviewed several studies that used the WAIS to assess cognitive functioning in healthy older adults and young patients with unilateral brain damage (e.g., Reed Jr & Reitan, 1963; Schaie & Schaie, 1977). Klisz observed that the WAIS performance of healthy older adults resembled that of young patients with right hemisphere damage. Both groups scored lower on the WAIS Performance IQ compared to the WAIS Verbal IQ. Based on these observations, Klisz concluded that "in older people there may be a greater decline of right hemisphere functions than of left hemisphere functions" (p. 83).

Goldstein and Shelly (1981) were the first to conduct a cross-sectional study, and empirically test the right-hemisphere ageing hypothesis. The researchers recruited 1247 participants across six age groups, ranging from individuals in their 20s to those in their 70s, and administered neuropsychological assessments, including the WAIS. Based on selected items from these neuropsychological assessments, they constructed separate scoring indices to estimate the degree of impaired functioning in the RH and LH. For example, impaired RH functioning was diagnosed when: WAIS Performance IQ was at least 10 points lower than WAIS Verbal IQ; somatosensory functions were poorer with the left hand than with the right hand; or performance on spatial relations tasks was lower

than on aphasia tasks. In contrast, impaired LH functioning was diagnosed when: WAIS Verbal IQ was at least 10 points lower than WAIS Performance IQ; somatosensory functions were poorer with the right hand than with the left hand; or performance on aphasia tasks was lower than on spatial relations tasks. Goldstein and Shelly reported that both impaired RH functioning scores and impaired LH functioning scores increased linearly with age. These findings were interpreted to mean that both RH functions and LH functions decrease with age to the same extent. Overall, Goldstein and Shelly concluded that their findings did not support the right-hemisphere ageing hypothesis.

Nevertheless, subsequent behavioural studies have investigated the right-hemisphere ageing hypothesis. These studies fall into three broad types, of which two types of studies have provided support for the right-hemisphere ageing hypothesis. The first type of behavioural study to provide support for the right-hemisphere ageing hypothesis concerns spatial attention to the LVF compared to the RVF, regardless of the type of information being processed in that visual field. Specifically, these studies compared the overall attention of young and older adults to information presented in the LVF (initially processed by the RH) *versus* the RVF (initially processed by the LH). These studies have typically argued that older adults demonstrate a rightward attentional bias compared to young adults. The logic is that the RH is more affected by ageing and thus less capable of processing information presented in the LVF. As a result, the attention of older adults is drawn to the information presented in the RVF, which is processed by the relatively intact LH. Supporting evidence for the right-hemisphere ageing hypothesis in this type of behavioural study includes research by Schmitz and Peigneux (2011) and by Guilbert et al. (2019). Schmitz and Peigneux used a perceptual landmark task, where participants were asked to judge whether the left half of a bisected line was longer or shorter than the right half. These researchers reported that, compared to young adults, older adults demonstrated a rightward attentional bias in this task, with the right half of lines perceived as being longer than the left half of lines. This age-related rightward attentional bias was interpreted as evidence that the RH is more vulnerable to age-related changes and thus less efficient at processing information presented in the LVF. In the study by Guilbert et al., Posner's spatial cueing paradigm (Posner, 1980; Posner et al., 1980) was adopted to examine age-related changes in attentional orienting to the LVF

versus the RVF. In a standard spatial cueing paradigm, two boxes are positioned to the left side of the central fixation (i.e., in the LVF) and to the right side (i.e., in the RVF). On each trial, a target appears in one of the boxes, preceded by a cue that either correctly indicates the target's location (valid-cue condition) or incorrectly indicates the opposite location (invalid-cue condition). The difference in reaction time between the valid-cue condition and the invalid-cue condition reflects participants' efficiency in disengaging attention from the cued location and re-orienting attention to the unexpected target location. Guilbert et al. reported that older adults demonstrated greater difficulty disengaging attention from a cue appearing in the RVF and re-orienting attention to a target appearing in the LVF, as compared to disengaging attention from a cue appearing in the LVF and re-orienting attention to a target appearing in the RVF. The implication from the findings of Guilbert et al. was that age-related attentional biases may relate to older adults' greater difficulties in disengaging attention from the RVF and re-orienting attention to the LVF.

The second type of behavioural study to provide support for the right-hemisphere ageing hypothesis compared young and older participants' overall performance on tasks assumed to rely primarily on RH functions *versus* those assumed to rely primarily on LH functions, without directly addressing whether hemispheric asymmetry was demonstrated for the tasks per se (i.e., whether there was a LVF/RH advantage for the RH-associated tasks and a RVF/LH advantage for the LH-associated tasks). Unlike the divided visual field design that directly examines hemispheric asymmetry through unilateral stimulus presentation, these studies presented stimuli centrally. The aim was to assess whether older participants demonstrated relatively greater age-related changes in overall performance on tasks associated with RH functions (e.g., visuospatial processing) compared to those associated with LH functions (e.g., verbal processing). For example, Jenkins et al. (2000) examined age-related differences between visuospatial processing and verbal processing using three different types of tasks: (1) speeded tasks; (2) working memory tasks; and (3) paired-associates learning tasks. The visuospatial stimuli or verbal stimuli were centrally presented. Task performance for visuospatial stimuli was assumed to be associated with RH functions, and task performance for verbal stimuli was assumed to be associated with LH functions. However, Jenkins et al.

did not validate whether hemispheric asymmetry was demonstrated for the visuospatial stimuli and for the verbal stimuli used across the three tasks. Jenkins et al. reported that older participants demonstrated overall worse performance across all three types of tasks compared to young participants. Crucially, within the older age group, performance was consistently worse on visuospatial stimuli compared to verbal stimuli, across all three types of tasks. These results were interpreted as evidence that the RH, which was assumed to specialise in processing the visuospatial stimuli used in the tasks, was more vulnerable to age-related changes than the LH, which was assumed to specialise in processing the verbal stimuli used in the tasks. These findings were interpreted as support for the right-hemisphere ageing hypothesis.

A similar conclusion to that of Jenkins et al. (2000) was reached in the study by Wang et al. (2019), in which young and older participants were presented with either a low spatial frequency face or a high spatial frequency face before making a size judgement on the Ebbinghaus illusion. Low spatial frequency information is associated with global processing, which is predominantly processed by the RH; whereas high spatial frequency information is associated with local processing, which is predominantly processed by the LH (Sergent, 1982). Performance on the Ebbinghaus illusion is known to be modulated by global-local processing, with greater susceptibility to the illusion linked to participants with a stronger global-processing bias (i.e., preference to attend globally as opposed to locally) (e.g., Phillips et al., 2004). However, as with the study by Jenkins et al., Wang et al. did not validate whether hemispheric asymmetry was demonstrated for the low spatial frequency faces and for the high spatial frequency faces used in the task. Wang et al. reported that young participants demonstrated increased susceptibility to the Ebbinghaus illusion following exposure to the low spatial frequency faces compared to the high spatial frequency faces. These findings were interpreted as evidence that the processing of the low spatial frequency faces elicited a processing bias towards global information, thus increasing susceptibility to the Ebbinghaus illusion. In contrast, older participants did not demonstrate a comparable increase in susceptibility to the Ebbinghaus illusion after exposure to the low spatial frequency faces, as compared to the high spatial frequency faces. These findings were interpreted to mean that exposure to low spatial frequency faces did not elicit a processing bias towards global information

in older participants. This was because older participants demonstrated difficulties in processing low spatial frequency faces due to greater age-related changes in RH functions.

The third type of behavioural study examined age-related changes in hemispheric asymmetry using the divided visual field design; however, many of these studies did not provide clear support for the right-hemisphere ageing hypothesis. These studies investigated whether young adults and older adults differ in their performance on tasks associated with RH function. Unlike the second type of behavioural study, which used centrally-presented stimuli to examine overall performance on RH-associated tasks or LH-associated tasks, this third type of behavioural study adopted a unilateral stimulus presentation (i.e., the divided visual field design) to examine hemispheric asymmetry directly. Two key distinctions can be made between behavioural studies using central stimulus presentation and unilateral stimulus presentation. First, studies using unilateral stimulus presentation typically begin by confirming hemispheric asymmetry in young adults. Specifically, whether young adults demonstrate better performance for RH-associated tasks when stimuli are presented in the LVF compared to the RVF, and whether young adults demonstrate better performance for LH-associated tasks when stimuli are presented in the RVF compared to the LVF. Second, once this hemispheric asymmetry is confirmed in young adults, these studies examined whether older adults demonstrated comparable or reduced RH functional specialisation as compared to young adults. This is typically assessed by comparing the performance of the two age groups on RH-associated tasks when stimuli are presented in the LVF as compared to the RVF. For example, Beaton et al. (2012) examined age-related changes in RH specialisation for facial emotion processing. Participants were shown a centrally-presented word, followed by a pair of eyes presented to either the LVF or to the RVF, and were asked to judge whether the word accurately described the emotional expression of the eyes. Both young participants and older participants demonstrated faster performance to the pair of eyes presented to the LVF compared to the RVF, suggesting RH specialisation for facial emotion processing. Importantly, the two age groups did not differ in this RH specialisation for emotion processing; specifically, the magnitude of the reaction time performance difference between the LVF and the RVF was equivalent for

the young and older participants. These findings, indicating that RH specialisation for facial emotion processing remains intact with age, did not provide support for the right-hemisphere ageing hypothesis.

In contrast, Prodan et al. (2007) reported findings that did support the right-hemisphere ageing hypothesis in the context of RH specialisation for facial emotion processing. In their task, young participants and older participants were shown a half-face stimulus depicting either the upper face or the lower face, which was presented to either the LVF or to the RVF. The half-face stimulus was followed by six full-face emotional expressions, and participants were instructed to make a verbal response indicating which one of the six full-face emotional expressions matched the half-face stimulus (i.e., either an upper face or a lower face). The researchers reported that young participants demonstrated more accurate performance in judging the emotional expression when the upper-face stimuli were presented to the LVF as compared to the RVF, suggesting RH specialisation for processing emotional information from the upper face. In contrast, older participants demonstrated an overall worse performance in judging the emotional expression of the upper face compared to young adults, with performance specifically reduced for upper-face stimuli presented to the LVF compared to the RVF. These findings indicated that RH specialisation for processing emotional information from the upper face is influenced by ageing, thus providing support for the right-hemisphere ageing hypothesis.

To the best of our knowledge, Oken et al. (1999) is the only study in the literature that represents the third type of behavioural study, examining age-related changes in hemispheric asymmetry specifically for a global-local processing task. They used Navon's (1977) hierarchical figures, in which a large object (i.e., the global level) was made up of several smaller objects (i.e., the local level). The hierarchical figures were presented to either the LVF or to the RVF. Participants were instructed to focus on either the global level or the local level to detect whether a target appeared. Oken et al. reported that both young participants and older participants demonstrated faster performance in detecting global targets presented to the LVF compared to the RVF, indicating RH specialisation for global processing. Both age groups also demonstrated faster

performance in detecting local targets presented to the RVF compared to the LVF, indicating LH specialisation for local processing. Importantly, the two age groups did not differ in RH specialisation for global processing; specifically, the magnitude of the reaction time performance difference between detecting global targets in the LVF compared to the RVF was equivalent for the young and older participants. These findings indicated that RH specialisation for global processing remains intact with age, which thus did not provide support for the right-hemisphere ageing hypothesis.

In summary, the right-hemisphere ageing hypothesis proposes that RH functions are more vulnerable to ageing when compared to LH functions. Although this hypothesis has been widely cited to explain age-related changes in hemispheric asymmetry, there are two major limitations. In regard to the first limitation, the main source of support for the right-hemisphere ageing hypothesis has largely come from two types of behavioural studies, neither of which directly examined age-related changes in hemispheric asymmetry. The first type of behavioural study examined age-related changes in overall performance (e.g., reaction time or accuracy) in the LVF (or the left side of an object) compared to the RVF (or the right side of an object), but did not link these visual field differences to specific cognitive functions associated with each of the two hemispheres (e.g., Guilbert et al., 2019; Schmitz & Peigneux, 2011). The second type of behavioural study examined age-related changes in overall performance on tasks assumed to measure RH functions (e.g., Jenkins et al., 2000; Wang et al., 2019), but did not validate whether these tasks actually demonstrated better performance when the processing occurred in the RH, such as by comparing performance in the LVF with that in the RVF using a divided visual field design. In regard to the second limitation, to the best of our knowledge, there is limited neuroimaging evidence providing structural or functional support for the right-hemisphere ageing hypothesis. While discussion of this second limitation is beyond the scope of this thesis, the empirical studies reported in Chapters 2, 3, and 4 focus on addressing the first limitation by examining the effects of healthy ageing on hemispheric asymmetry in global-local processing. This will be achieved using a behavioural paradigm based on the divided visual field design, in which Navon's (1977) hierarchical figures were unilaterally presented to either the LVF or the RVF. This setup enables direct investigation of age-related changes in RH specialisation for global

processing (i.e., performance in detecting global targets presented in the LVF compared to the RVF) and LH specialisation for local processing (i.e., performance in detecting local targets presented in the RVF compared to the LVF).

The HAROLD Model. The 'Hemispheric Asymmetry Reduction in Older Adults' (HAROLD) model proposes that there is a reduction in hemispheric lateralisation for cognitive processing in the prefrontal cortex. That is, older adults tend to recruit both hemispheres to process tasks associated with prefrontal functions, which are typically processed by one hemisphere in young adults. The model first proposed by Cabeza (2002) was based on neuroimaging evidence from studies on episodic memory. In young participants, episodic memory retrieval was associated with greater activation in the right prefrontal cortex, while episodic memory encoding was associated with greater activation in the left prefrontal cortex. In contrast, older participants demonstrated bilateral prefrontal activation during episodic memory retrieval as well as an overall reduction in prefrontal activation during episodic memory encoding (e.g., Bäckman et al., 1997; Cabeza et al., 1997). Cabeza (2002) interpreted these findings as evidence of an age-related reduction in hemispheric asymmetry for prefrontal functions. Cabeza further argued that similar patterns of reduced hemispheric asymmetry have been observed in older adults across a range of cognitive functions related to the prefrontal cortex, including semantic memory (e.g., Stebbins et al., 2002), working memory (e.g., Reuter-Lorenz et al., 2000), perceptual decision making (e.g., Grady et al., 2000), and inhibitory control (e.g., Nielson et al., 2002), providing further support for the HAROLD model.

It is important to note that the right-hemisphere ageing hypothesis and the HAROLD model are not mutually exclusive; rather, they account for age-related changes in functional hemispheric asymmetry across different cortical regions (Dolcos et al., 2002). The right-hemisphere ageing hypothesis concerns age-related changes in hemispheric asymmetry across the entire RH as compared to the LH, with particular emphasis on functions related to the posterior brain regions, such as the temporal and occipital regions. In contrast, the HAROLD model concerns age-related reductions in hemispheric asymmetry for functions related to the prefrontal cortex. As this thesis investigates age-related changes in hemispheric asymmetry for global-local processing, a visual attention

process primarily associated with the temporal-parietal regions (e.g., Fink et al., 1996; Fink et al., 1997), it will specifically address the explanatory scope of the right-hemisphere ageing hypothesis.

1.3.3 Does Functional Hemispheric Asymmetry Vary Across Individuals?

There are considerable individual differences in patterns of hemispheric asymmetry, diverging from what is often considered the 'prototypical' pattern (e.g., RH specialisation for global processing, LH specialisation for local processing). In fact, much of the existing research on the 'prototypical' hemispheric asymmetry is conducted exclusively with right-handed participants to control for such individual differences. These individual differences are commonly discussed along two key dimensions: (1) direction of the hemispheric asymmetry, and (2) magnitude of the hemispheric asymmetry (see Hellige, 1993 for a discussion on the other dimensions).

The first dimension concerns individual differences that are to do with the direction of the hemispheric asymmetry. That is, while many individuals demonstrate the 'prototypical' pattern of hemispheric asymmetry, some demonstrate a reversal of this pattern. For example, in the context of hemispheric asymmetry for global-local processing examined by a divided visual field design, the 'prototypical' pattern involves better performance for detecting global targets in the LVF compared to the RVF (i.e., RH-global specialisation) and local targets in the RVF compared to the LVF (i.e., LH-local specialisation). In contrast, some individuals may demonstrate a reversal of this 'prototypical' pattern, involving better performance for detecting global targets in the RVF compared to the LVF (i.e., *LH*-global specialisation) and local targets in the LVF compared to the RVF (i.e., *RH*-local specialisation).

The second dimension concerns individual differences that are to do with the magnitude of the hemispheric asymmetry. It is generally assumed that both hemispheres are capable of processing the same type of information, but one hemisphere may do so more efficiently than the other (see Section 1.3.4 for a more detailed review). The extent of this difference in efficiency between the two hemispheres can vary across individuals. For example, in the context of hemispheric asymmetry for global-local processing

examined by a divided visual field design, some individuals may demonstrate a stronger RH lateralisation for global processing, as indicated by greater performance differences between the detection of global targets presented to the LVF compared to the RVF. Likewise, some individuals may demonstrate a stronger LH lateralisation for local processing, as indicated by greater performance differences between the detection of local targets presented to the RVF compared to the LVF. Research on individual differences in hemispheric asymmetry has focused on identifying factors that modulate the direction or the magnitude of hemispheric asymmetry, with handedness and sex being the two most commonly examined factors.

1.3.3.1 Handedness. Hand preference is a widely discussed factor in the study of hemispheric asymmetry, as handedness represents not only a behavioural manifestation of hemispheric asymmetry, but it is also thought to modulate hemispheric asymmetry for other cognitive components (Hellige, 1993). Handedness is considered a behavioural manifestation of hemispheric asymmetry because a consistent preference for using one hand for motor actions indicates that motor functions may be primarily controlled by the contralateral hemisphere (also see Wang & Sainburg, 2007).

In addition, handedness has been argued to modulate functional hemispheric asymmetry. In particular, it has been proposed that handedness is associated with individual differences in the direction of the hemispheric asymmetry for language processing. Most of the human population is right-handed and demonstrates LH specialisation for language processing, leading to the proposal that these two traits may share a common evolutionary basis. Specifically, it has been suggested that human language is thought to have originated from manual gestures primarily produced by the right hand, with vocal articulation developed at a later stage (Corballis, 2003; Corballis et al., 2012). As such, it has long been assumed that handedness is a direct behavioural indicator for individual differences in the direction of the hemispheric asymmetry for language processing, such that right-handers demonstrate LH specialisation for language processing, whereas left-handers demonstrate RH specialisation for language processing. However, the relationship between handedness and hemispheric asymmetry for language processing is now known to be more nuanced. Although

handedness is correlated with hemispheric asymmetry for language processing, this correlation is weak and not perfect (Corballis, 2019; Corballis et al., 2012). Neuroimaging studies suggest that 95% to 99% of right-handers demonstrate LH specialisation for language processing, but so do 70% to 80% of left-handers (e.g., Badzakova-Trajkov et al., 2010). Similarly, neuropsychological case studies have been reported of left-handed individuals who develop aphasia following LH damage (e.g., Borod et al., 1985; Naeser & Borod, 1986), further confirming that handedness does not reliably predict the direction of the hemispheric asymmetry for language processing at the individual level.

A follow-up question to ask is whether handedness is related to individual differences in hemispheric asymmetry for cognitive components other than language processing. It has been suggested that individual differences in the direction of hemispheric asymmetry for one cognitive component may be indicative of individual differences in hemispheric asymmetry for other cognitive components (Hellige, 1993). Brederoo et al. (2020) examined this possibility by investigating hemispheric asymmetry across several cognitive components, including global-local processing, face and word recognition, and the processing of low and high spatial frequency information. The study used a divided visual field design, in which stimuli were presented unilaterally, to either the LVF or to the RVF. Participants were divided into three groups: (1) right-handers (N = 69); (2) left-handers with LH specialisation for language processing (N = 40); and (3) left-handers with RH specialisation for language, as determined by neuroimaging (N = 13). Brederoo et al. reported that right-handers and left-handers with LH specialisation for language processing did not differ in the direction of the hemispheric asymmetry across most of the cognitive components examined. Specifically, both groups demonstrated RH specialisation (i.e., better performance for detecting stimuli in the LVF compared to the RVF) for global processing and face processing, and LH specialisation (i.e., better performance for detecting stimuli in the RVF compared to the LVF) for word processing, local processing, and the processing of high spatial frequency information. However, some differences emerged in the magnitude of hemispheric asymmetry between these two groups. Right-handers demonstrated greater RH specialisation for face processing and for the processing of low spatial frequency information, when compared to left-handers with LH specialisation for language processing. In contrast, the third group of

left-handers with RH language specialisation did not demonstrate a reversal of the 'prototypical' hemispheric asymmetry pattern but instead demonstrated reduced hemispheric asymmetry across the cognitive components tested.

In summary, handedness is closely related to hemispheric asymmetry, particularly concerning LH specialisation for language processing. Although the influence of handedness on hemispheric asymmetry seems modest, left-handers do tend to show greater individual differences in both the direction and the magnitude of the hemispheric asymmetry across different cognitive components compared to right-handers. Accordingly, the present thesis focuses on examining hemispheric asymmetry for global-local processing in right-handed individuals. Participants' handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971), which required participants to indicate their preferred hand for various everyday activities (e.g., writing, drawing, throwing, using scissors, brushing teeth), as well as their preferred foot for kicking, and their preferred eye for monocular tasks.

1.3.3.2 Sex. Sex differences in hemispheric asymmetry have long been proposed, particularly concerning differences in the magnitude of the hemispheric asymmetry. Specifically, it has been proposed that males tend to demonstrate greater lateralisation than females. This proposal has often been used to explain observations of sex differences in overall task performance for visuospatial processing and for verbal processing (see Grabowska et al., 1994; Hirnstein et al., 2019). In these studies, performance for visuospatial processing is commonly examined using mental rotation tasks. In a typical version of the mental rotation task, participants are first shown either a two-dimensional (e.g., Rilea, 2008) or three-dimensional geometric figure (e.g., Peters et al., 1995; Vandenberg & Kuse, 1978), followed by one comparison figure or multiple comparison figures. Participants are then asked either to judge whether the comparison figure is a rotated version of the original figure or to select which of the comparison figures corresponds to a rotated version of the original figure. It has been reported that males demonstrate better overall performance in the mental rotation tasks compared to females (e.g., Linn & Petersen, 1985; Voyer et al., 1995; Zell et al., 2015). These findings were interpreted to mean that males demonstrate better performance for visuospatial

processing compared to females. On the other hand, performance for verbal processing is commonly examined using verbal fluency tasks, in which participants are instructed to generate as many words as possible that begin with a specified letter (e.g., words beginning with the letter "B") within a given time frame. It has been reported that females demonstrate better overall performance in verbal fluency tasks compared to males (e.g., Hyde & Linn, 1988). These findings were interpreted to mean that females demonstrate better performance for verbal processing.

Levy (1969, 1972, 1978) was the first to propose that the observed sex differences in overall performance for visuospatial processing and verbal processing may be attributed to sex differences in the magnitude of hemispheric asymmetry. Levy argued that males demonstrated greater lateralisation compared to females, with the RH more specialised for visuospatial processing. In contrast, females were proposed to be less lateralised, tending to recruit both hemispheres during verbal processing. Based on this proposal, males were predicted to perform better on visuospatial tasks due to greater RH lateralisation in visuospatial processing, whereas females were predicted to perform better on verbal tasks due to greater bilateral involvement in verbal processing. To examine Levy's proposal, Hirnstein et al. (2019) conducted a systematic review of behavioural, electrophysiological, and neuroimaging studies published over the past 40 years that examined sex differences in two dimensions: (1) overall performance on tasks examining visuospatial processing and verbal processing, and (2) the magnitude of hemispheric asymmetry for visuospatial processing and verbal processing. The systematic review revealed inconsistent findings across studies regarding both dimensions. Specifically, observed sex differences in overall performance for visuospatial tasks and verbal tasks were often not accompanied by sex differences in the magnitude of the hemispheric asymmetry for the corresponding tasks, and vice versa. Based on this pattern of results, Hirnstein et al. concluded that the available evidence does not support Levy's proposal that sex differences in overall performance for visuospatial processing and verbal processing can be explained by sex differences in the magnitude of the hemispheric asymmetry.

For face processing, findings on sex differences in the magnitude of the hemispheric asymmetry have been more consistent, supporting the view that males are more lateralised than females. Behavioural studies (e.g., Bourne, 2005; Godard & Fiori, 2010) have reported that males demonstrate greater performance differences between the LVF and RVF in face recognition tasks compared to females, suggesting stronger RH lateralisation for face processing in males. Likewise, event-related potentials studies (e.g., Prodan et al., 2007; Proverbio, 2021) have reported that males demonstrate greater RH lateralised activation during face processing, while females demonstrate more bilateral activation.

In contrast, findings regarding sex differences in the magnitude of the hemispheric asymmetry for global-local processing do not support the view that males are generally more lateralised than females. To the best of our knowledge, only two studies have examined sex differences in hemispheric symmetry for global-local processing. Roalf et al. (2006) conducted an event-related potentials study and found that it was females, rather than males, who demonstrated greater LH lateralised activation for local processing at the P100 component, whereas neither sex demonstrated significant RH specialisation for global processing. Hausinger and Pletzer (2021) conducted a behavioural study and found no significant sex differences in either the magnitude of RH specialisation for global processing or the magnitude of LH specialisation for local processing.

In summary, sex has primarily been proposed to account for individual differences in the magnitude of the hemispheric asymmetry, with males demonstrating greater lateralisation compared to females. This proposal was initially put forward to explain sex differences in overall performance for visuospatial processing and verbal processing. However, behavioural and neuroimaging evidence concerning hemispheric asymmetry for both visuospatial-verbal processing and global-local processing has either been inconsistent or does not support this proposal. Given the lack of conclusive evidence for sex differences in hemispheric asymmetry, both male and female participants will be recruited for the empirical studies in this thesis to maximise the number of participants included. Appendix B of this thesis will present data from 127 young participants (70

young females, 57 young males) and 58 older participants (39 older females, 19 older males) to examine whether sex influences findings for hemispheric asymmetry for global-local processing.

Thus far, in this section of the introduction, the influence of handedness and sex on individual differences in hemispheric asymmetry was reviewed. Much of the other existing literature on individual differences in hemispheric asymmetry focused on identifying between-group factors that modulate either the direction or the magnitude of the hemispheric asymmetry. However, one question that remains open is the extent to which within-group individual differences in hemispheric asymmetry exist, specifically when measured using the divided visual field design, which has unilateral stimulus presentation to the LVF or to the RVF and thus allows for the most direct examination of RH specialisation for global processing and LH specialisation for local processing. Chapter 4 of this thesis will address this question.

1.3.4 What are the Theoretical Interpretations of these Hemispheric Asymmetry Findings?

Two major theoretical models have been proposed to account for the empirical findings on hemispheric asymmetry: the structural model (Cohen, 1982) and the attentional model (Kinsbourne, 1970, 1973). The structural model posits that hemispheric asymmetry arises from anatomical differences between the two hemispheres, such that specific neural structures (particularly those involving cognitive functions) are more developed in one hemisphere than in the other hemisphere. As a result, one hemisphere becomes more specialised for performing those cognitive functions relative to the other hemisphere. Within the structural model, two subtypes have been identified based on the degree of specialisation: the absolute structural model and the relative structural model.

The absolute structural model (Cohen, 1982) proposes that a lateralised cognitive function is strictly processed in the 'specialist' hemisphere. Accordingly, when stimuli are presented to the 'non-specialist' hemisphere, the information must be transferred via the corpus callosum to the 'specialist' hemisphere for processing. In the context of a divided visual field design, the absolute structural model predicts that both the direction

and the magnitude of the hemispheric asymmetry would remain fixed. That is, performance would consistently be better when stimuli are presented to the 'specialist' visual field compared to the 'non-specialist' visual field. Moreover, any delayed response when stimuli are presented to the 'non-specialist' visual field as compared to the 'specialist' visual field would reflect the interhemispheric transfer time required for transferring information from the 'non-specialist' hemisphere to the 'specialist' hemisphere.

In contrast, the relative structural model (Cohen, 1982) proposes that a lateralised cognitive function is not exclusively processed in one hemisphere. Instead, both hemispheres are capable of processing the relevant information, but one hemisphere does so more efficiently than the other hemisphere. In the context of a divided visual field design, the relative structural model predicts better performance for stimuli presented to the 'specialist' visual field as compared to the 'non-specialist' visual field. The relative performance difference between the two visual fields thus reflects the extent to which one hemisphere is more efficient than the other in processing that particular cognitive function.

The absolute structural model is not supported by the majority of empirical evidence. As previously discussed (in Section 1.3.4), the early dichotomous approach in hemispheric asymmetry research supports the absolute structural model, assuming that specific cognitive functions are strictly processed in one hemisphere (Christman, 2024; Hellige, 1993). The dichotomous approach has since been challenged by the componential approach, which supports the relative structural model and emphasises differences in relative processing efficiency between the two hemispheres. For instance, verbal processing is widely recognised to be predominantly associated with the LH. According to the absolute structural model, this hemispheric asymmetry would be interpreted as meaning that verbal information is being strictly processed in the LH. However, findings from split-brain patient studies have indicated that the RH processes some aspects of verbal comprehension, as evidenced by split-brain patients being able to name (Baynes et al., 1995) or point to (Gazzaniga et al., 1977) picture or word stimuli presented to the LVF/RH. Similarly, neuroimaging studies in healthy right-handed

individuals have revealed that while the LH predominantly processes verbal information, the RH contributes to the processing of phonological information and contextual integration (see Lindell, 2006 for a review; Vigneau et al., 2011). These findings support the relative structural model, which assumes differential processing efficiency between the two hemispheres.

Despite extensive empirical support for the relative structural model, Cohen (1982) identified two key limitations. First, the relative structural model does not adequately account for fluctuation in the magnitude of hemispheric asymmetry within the same individual across time (e.g., across different trials or blocks). That is, although an individual may demonstrate an overall performance advantage in one visual field over the other visual field when averaged across all trials, their performance difference between the two visual fields can vary across smaller trial segments or blocks. For instance, a participant might show a strong lateralisation effect during one block but a reduced or even reversed pattern in another block. Second, the relative structural model assumes that there is no transfer of information between the two hemispheres and thus does not account for the role of the corpus callosum in interhemispheric information transfer. At least in the context of the divided visual field paradigm using unilateral stimulus presentation, the relative structural model assumes that performance in one visual field reflects the full capacity of the contralateral hemisphere. However, it is likely that some of the information presented in any given visual field is transferred to the ipsilateral hemisphere via the corpus callosum. Thus, interhemispheric communication may contribute to task performance in any given visual field.

In addition to the structural model, the attentional model (Kinsbourne, 1970, 1973) is another theoretical model that has been proposed to account for the empirical findings on hemispheric asymmetry. While proponents of the attentional model acknowledge that structural differences between the two hemispheres contribute to functional hemispheric asymmetry (as proposed by the structural model), they argue that such structural differences account for only a small and stable proportion of hemispheric asymmetry. Instead, the attentional model proposes that a large and variable proportion of hemispheric asymmetry arises from fluctuations in attentional allocation between the

two hemispheres. The proposal is that increased attentional allocation to one hemisphere enhances its perceptual readiness or processing capacity, leading to improved performance for stimuli presented in the contralateral visual field.

One key factor discussed within the attentional model is the effect of stimulus category on attentional allocation across the two hemispheres (see Cohen, 1982 for a review of the other factors). In Kinsbourne's (1970) study, participants performed a gap-detection task while simultaneously performing a verbal memory task. First, participants were asked to memorise a list of six one-syllable words. Then, a square was presented centrally on the screen, with a gap located either on the left side or the right side of the square's outline. If the gap appeared on the right side of the square (positioned in the RVF), participants were instructed to recall the first three words from the list; whereas if the gap appeared on the left side of the square (positioned in the LVF), they were asked to recall the last three words from the list. Participants demonstrated better recall performance following detection of a gap on the right side of the square compared to the left side of the square. Kinsbourne interpreted this finding as evidence that maintaining verbal information in working memory enhances perceptual readiness in the LH (where verbal processing is typically specialised), thereby improving recall performance when attention is directed to the RVF (i.e., detecting a gap at the right side of the square). There is one methodological limitation to this finding: participants were always asked to recall the first three words when the gap appeared on the right side of the square, and to recall the last three words when the gap appeared on the left side of the square. This lack of counterbalancing may have led to better recall performance following detection of a gap on the right side of the square, as the first few words in a list are generally easier to recall.

Nevertheless, subsequent studies provided further support for the influence of stimulus category on attentional allocation between the two hemispheres and the corresponding contralateral visual field. For example, in the study by Cohen (1975), participants were presented with a mixed series of digit stimuli, word stimuli, and dot stimuli, presented either in the LVF or in the RVF. Their task was to judge whether the presented stimulus represented the number four or five (i.e., the digit "4" or "5"; the word "four" or "five"; the array of four dots or five dots). Two types of trial conditions were used:

an uncued condition and a cued condition. In the uncued condition, no information was provided prior to stimulus onset. Whereas in the cued condition, a cue was provided prior to stimulus onset to indicate the nature of the upcoming stimulus (i.e., whether it was in the format of a digit, word, or dot). Cohen reported that in the uncued condition, participants demonstrated no significant performance difference between the two visual fields. However, in the cued condition, participants were more accurate in judging word stimuli presented in the RVF/LH compared to the LVF/RH, suggesting that a cue indicating the verbal nature of the upcoming stimulus increased perceptual readiness in the LH. Likewise, in the cued condition, participants were more accurate in judging dot stimuli presented in the LVF/RH compared to the RVF/LH, suggesting that a cue indicating the visuospatial nature of the upcoming stimulus increased perceptual readiness in the RH.

An important implication drawn from the effect of stimulus category discussed within the attentional model is that hemispheric asymmetry for different cognitive components may be influenced by the stimulus category employed. Specifically, the verbal processing or visuospatial processing demands inherent to a stimulus category may modulate attentional allocation between the two hemispheres. For example, letter stimuli that involve higher demands for verbal processing may enhance the processing efficiency or perceptual readiness of the LH, whereas object stimuli that involve higher demands for visuospatial processing may enhance the processing efficiency or perceptual readiness of the RH. This potential influence may inadvertently affect results when examining hemispheric asymmetry for different cognitive components, including research on global-local processing.

As introduced earlier, hemispheric asymmetry for global-local processing is commonly studied using the divided visual field design, in which a hierarchical figure (Navon, 1977) is presented unilaterally to either the LVF or the RVF. What is typically reported is that participants demonstrate better performance for detecting the global targets presented in the LVF/RH compared to the RVF/LH (indicating RH specialisation for global processing) and better performance for detecting the local targets presented in the RVF/LH compared to the LVF/RH (indicating LH specialisation for local processing)

(e.g., Hübner, 1998; Martin, 1979; Sergent, 1982; Yovel et al., 2001). However, most of these findings come from studies using hierarchical figures composed of letters. It has been argued that the observed LH-local specialisation in such studies may be partly driven by the greater involvement of the LH in verbal processing. Consistent with the attentional model, stimulus category has been shown to influence hemispheric asymmetry for global-local processing. Specifically, a reversed pattern of RH specialisation for *local* processing and LH specialisation for *global* processing has been observed when using hierarchical figures composed of objects, which involves greater demands on visuospatial processing (Fink et al., 1997; Kéïta & Bedoin, 2011). Chapter 2 of this thesis presents an empirical study that examines whether stimulus category influences hemispheric asymmetry for global-local processing. Hierarchical figures were constructed using three stimulus categories that differ in their visuospatial-verbal processing demands: letters, verbalisable objects, and nonverbalisable shapes.

1.4 Chapter Summary

In this chapter, I first provided an historical review of functional hemispheric asymmetry, beginning with ancient conceptions of the heart as the seat of the soul, and I then traced the gradual shift toward recognising the brain as the locus of the mind. I reviewed how early anatomical and speculative perspectives, including Descartes' localisation of the soul in the pineal gland and the influence of phrenology, shaped emerging views of brain function. Importantly, these early perspectives assumed hemispheric *symmetry*, with both sides of the brain considered functionally identical.

I then reviewed the emergence of the modern concept of functional hemispheric asymmetry, from clinical case studies by Broca and Wernicke to the development of experiment paradigms in the 20th century, including the dichotic listening paradigm and the divided visual field design. In particular, these experimental paradigms enabled non-invasive and systematic investigations into functional differences between the two hemispheres and led to a surge of research in the field. I reviewed the dominance of the dichotomous approach in early hemispheric asymmetry research, which assumed that each hemisphere was exclusively specialised for particular types of cognitive processing.

The dichotomies proposed, such as visuospatial-verbal processing or holistic-analytic processing, were later criticised for oversimplifying functional specialisation and lacking consistent operationalisation. As evidence accumulated, the field shifted toward a componential approach, which proposes that both hemispheres contribute to the processing of most types of cognitive components but differ in processing efficiency. Within this approach, global-local processing is one of the most extensively studied components for investigating hemispheric asymmetry in visual attention, with Navon's (1977) hierarchical figures typically used to operationalise task performance at the global level and local level of visual processing.

Finally, I reviewed four key aspects of hemispheric asymmetry. First, I reviewed the evolutionary origins of hemispheric asymmetry, which suggests that it may have developed as an adaptive response to survival demands. Second, I reviewed major theories proposed for the developmental trajectories of hemispheric asymmetry. In early development, it is proposed that RH functions mature earlier than LH functions. In older adults, RH functions, particularly those associated with posterior regions of the brain, are thought to be more susceptible to age-related changes than LH functions; while functions associated with the prefrontal cortex demonstrate an age-related reduction in lateralisation. Third, I reviewed studies investigating individual differences in hemispheric asymmetry, focusing on the two factors of handedness and sex. Left-handers tend to demonstrate greater individual differences in the direction and the magnitude of the hemispheric asymmetry across various cognitive components compared to right-handers, whereas findings regarding sex differences have been inconsistent. Fourth, I reviewed two major accounts for interpreting findings of hemispheric asymmetry: the structural model and the attentional model. The structural model proposes that hemispheric asymmetry primarily reflects anatomical differences between the two hemispheres. In contrast, the attentional model suggests that a large and variable proportion of hemispheric asymmetry arises from fluctuations in attentional allocation between the two hemispheres, with stimulus category identified as a key factor that may modulate this attentional allocation.

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Chapter 2 Hemispheric Asymmetry for Global-Local Processing: Effects of Stimulus Category and Ageing

Publication Note

The study presented in this chapter has been published as:

Chen, H., Cox, J. A., & Aimola Davies, A. M. (2024). Hemispheric asymmetry for global-local processing: Effects of stimulus category and ageing. *Quarterly Journal of Experimental Psychology*, *78*(8), 1627-1648. https://doi.org/10.1177/17470218241280800

Abstract

Hemispheric asymmetry has been reported for global-local processing in young and older adults, with global processing specialised in the right hemisphere (RH-global specialisation) and local processing specialised in the left hemisphere (LH-local specialisation). Questions persist regarding the extent to which hemispheric asymmetry is influenced by stimulus category (verbal stimuli processed in the left hemisphere; visuospatial stimuli processed in the right hemisphere). Some evidence suggests stimulus category does not influence hemispheric asymmetry (stimulus-independent account), while other evidence suggests it does (stimulus-dependent account). In older adults, there is evidence of a local-processing bias, believed to result from slower and less accurate performance in right-hemisphere compared to left-hemisphere functioning—the right-hemisphere ageing hypothesis. We examined hemispheric asymmetry for global-local processing in young and older participants with three hierarchical figures (letters, verbalisable objects, and nonverbalisable shapes), in a within-subjects design using a divided-attention paradigm and unilateral presentation. Our findings for letters and verbalisable objects support the stimulus-independent account—young and older participants demonstrated RH-global specialisation and LH-

local specialisation regardless of stimulus category. In older participants, we also found a local-processing bias for all three stimulus categories—a bias best explained as faster and more accurate performance in local processing regardless of the visual field of stimulus presentation. Overall, we found hemispheric asymmetry for global-local processing in both young and older adults, and differences in global processing between young and older adults. Future investigation is suggested for the hemispheric asymmetry found in global-local processing of nonverbalisable shapes, and the mechanisms underlying age-related changes in global processing.

2.1 Introduction

Our visual environment consists of hierarchical structures. For instance, a scene with many trees can be perceived as either an entire forest or as individual trees within the forest. To navigate in such a complex visual environment, our visual system relies on visual attentional mechanisms to process relevant information selectively (Carrasco, 2011). One such mechanism is global-local processing, which involves directing attention either globally (e.g., to the overall visual scene, such as the forest) or locally (e.g., to the finer elements within the scene, such as individual trees or even the leaves on a tree). Hemispheric asymmetry has been demonstrated for global-local processing (Yovel et al., 2001), with the right hemisphere (RH) specialised for global processing (i.e., RH-global specialisation) and the left hemisphere (LH) specialised for local processing (i.e., LH-local specialisation). Navon's (1977) hierarchical figures, in which a large stimulus is made up of several smaller stimuli (e.g., a large global letter "U" is made up of smaller local letters "T"), has been widely used to study hemispheric asymmetry for global-local processing.

Hemispheric asymmetry for global-local processing has been demonstrated in neuropsychological studies, neuroimaging studies and behavioural studies. Neuropsychological studies have demonstrated that patients with lesions to their RH exhibit deficits in global processing, whereas patients with lesions to their LH exhibit deficits in local processing (e.g., Delis et al., 1986; Lamb et al., 1990; Robertson et al., 1988). Neuroimaging studies with healthy young adults further support the finding of

hemispheric asymmetry for global-local processing by demonstrating greater RH activation for global processing and greater LH activation for local processing (e.g., Fink et al., 1996; Fink, Halligan et al., 1997; Martens & Hübner, 2013; Martinez et al., 1997). Behavioural studies, using a hierarchical-figures paradigm, within a divided visual field presentation, have provided additional support by demonstrating both reaction time (RT) and accuracy differences for global-local processing in the two hemispheres. For example, RT differences in hemispheric asymmetry were found by Hübner (1998), Sergent (1982), Van Kleeck (1989), and Yovel et al. (2001), and accuracy differences were found by Brederoo et al. (2017). The logic behind using the divided visual field presentation was that hierarchical stimuli briefly presented unilaterally to the left visual field (LVF) would be processed first by the RH, and hierarchical stimuli briefly presented unilaterally to the right visual field (RVF) would be processed first by the LH (Bourne, 2006). In these behavioural studies, RH-global specialisation was indicated by faster RT and/or higher accuracy for the global-level stimuli presented in the LVF/RH compared to the RVF/LH, and LH-local specialisation was indicated by faster RT and/or higher accuracy for the local-level stimuli presented in the RVF/LH compared to the LVF/RH.

2.1.1 Effects of Stimulus Category

Previous research on RH-global specialisation and LH-local specialisation has primarily been based on hierarchical figures made up of letters (see Yovel et al., 2001). It has been suggested that the observed hemispheric asymmetry for global-local processing may be influenced by the stimulus category itself (Fink, Marshall, et al., 1997; Kéïta & Bedoin, 2011), as the LH is more specialised for verbal processing (e.g., letters) and the RH is more specialised for visuospatial processing (e.g., objects and shapes; see Dien, 2009). Specifically, the proposal is that the LH-local specialisation observed in studies using letters may have been driven by greater involvement of the LH in processing the letters (Fink, Marshall, et al., 1997). Five studies have addressed this hypothesis by directly comparing findings from hierarchical letters with those from hierarchical objects (see Table 2.1 for a summary), leading to two contrasting accounts: a *stimulus-independent* account and a *stimulus-dependent* account.

Supporters of the stimulus-independent account have argued that hemispheric asymmetry for global-local processing is not influenced by stimulus category. Brederoo et al. (2017) examined hemispheric asymmetry for global-local processing using hierarchical letters and hierarchical objects made up of geometric figures (e.g., crosses, rectangles, and diamonds). Their accuracy data demonstrated RH-global specialisation and LH-local specialisation for both letters and objects (also see Bedson & Turnbull, 2002). The stimulus-independent account is explained by the double-filtering by frequency theory (Ivry & Robertson, 1998), which posits that the selection of visual information occurs in two stages (Flevaris & Robertson, 2016), starting with the selection of a specific range of spatial frequencies from incoming spectra, and followed by processing of low spatial frequencies in the RH and high spatial frequencies in the LH (see also Sergent, 1982). Brederoo et al. further argued that the processing of low spatial frequencies in the RH results in RH-global specialisation and the processing of high spatial frequencies in the LH results in LH-local specialisation. This hemispheric asymmetry for global-local processing can be observed across different stimulus categories, as long as they have similar spatial frequency spectra. That is, the global level of a hierarchical figure, irrespective of stimulus category, is always specified by low spatial frequencies, and the local level is always specified by high spatial frequencies.

Supporters of the stimulus-dependent account have argued that stimulus categories with higher demands for visuospatial processing reverse the hemispheric asymmetry for global-local processing, resulting in RH-*local* specialisation and LH-*global* specialisation for objects. Two consecutive neuroimaging studies compared hierarchical letters (Fink, Halligan, et al., 1997) and hierarchical objects made up of familiar figures (e.g., hearts and stars; Fink, Marshall, et al., 1997). Behavioural data were not reported in these studies, but the neuroimaging data revealed that, for letters, there was RH-global specialisation and LH-local specialisation; whereas, for objects, the pattern of hemispheric asymmetry was reversed, revealing RH-*local* specialisation and LH-*global* specialisation. Fink, Marshall, et al. (1997) proposed that this reversal of hemispheric specialisation could be explained by a top-down process that automatically assigns local processing to the hemisphere specialised for the verbal or visuospatial information involved in the stimulus, while assigning global processing to the other hemisphere. Kéïta

and Bedoin (2011) replicated these findings with behavioural data, by comparing participants' RT and accuracy performance on hierarchical letters and hierarchical objects made up of familiar figures (e.g., hearts and stars). For letters, Kéïta and Bedoin demonstrated RH-global specialisation (as indicated by their RT data) and LH-local specialisation (as indicated by their accuracy data); whereas, for objects, only the accuracy data supported the reverse pattern of RH-*local* specialisation and LH-*global* specialisation.

The researchers (Brederoo et al., 2017; Fink, Halligan, et al., 1997; Fink, Marshall, et al., 1997; Kéïta & Bedoin, 2011) who have directly investigated the effects of stimulus category proposed that only visuospatial processing was required for their hierarchical objects, but it is worth noting that these hierarchical objects were made up of familiar verbalisable objects that could be associated with verbal labels. Only two studies (Johannes et al., 1996; Martinez et al., 1997) have investigated hemispheric asymmetry for global-local processing using novel nonverbalisable shapes, to which verbal labels could not easily be applied. Johannes et al. (1996) used electrophysiological measures and reported a LH advantage for global and local nonverbalisable shapes, thus not finding support for either the stimulus-independent or stimulus-dependent accounts. Martinez et al. (1997) used both behavioural and neuroimaging measures and found support for the stimulus-independent account in their neuroimaging data (i.e., RH activation for global nonverbalisable shapes and LH activation for local nonverbalisable shapes, with the strength of the RH-global activation greater than that of the LH-local activation). In their behavioural data, they reported LH-local specialisation for nonverbalisable shapes in the absence of RH-global specialisation. Neither study included a control stimulus category (i.e., neither letters nor verbalisable objects) when examining hemispheric asymmetry in global-local processing across different stimulus categories. Consequently, questions remain about the two theoretical accounts for the effect of stimulus category.

Table 2.1

Methodological Differences in Studies Examining the Effects of Stimulus Category

	Study	Young Participants *N* / Age	Measures	Stimulus category	Stimulus size (degree)		Local-level density	Stimulus presentation	Eccentricity (° from fixation)	Presentation duration	Task type	Response mode	Dependent variable	Hemispheric asymmetry findings	
					Global size	Local size								RH specialisation	LH specialisation
1	Johannes et al. (1996)	*N* = 13 / 26.7 years	Neuroimaging	Shapes	7.20°×7.20°	1.16°×1.16°	17	Central	NA	100ms	Divided	Go/No-go	ERP amplitude	—	—
2	Martinez et al. (1997)	*N* = 11 / 27 years	Behavioural	Shapes	2.30°×3.60°	0.29°×0.45°	16	Unilateral/ Central	NR	50ms	Focused	Go/No-go	RT	—	+ LH-local
			Neuroimaging	Shapes	2.30°×3.60°	0.29°×0.45°	16	Central	NA	50ms	Focused	Mental counting[a]	Area of activation	+ RH-global	+ LH-local
3	Fink, Halligan, et al. (1997)	*N* = 10 / 19–35 years	Neuroimaging	Letters	10.00°×24.00°	1.86°×3.01°	11–18	Central	NA	300ms	Focused	Naming	RBF	+ RH-global	+ LH-local
4	Fink, Marshall, et al. (1997)	*N* = 10 / 19–32 years	Neuroimaging	Objects	16.00°×16.00°	1.00°×1.00°	47–49	Central	NA	300ms	Focused	Naming	RBF	**+ RH-local**	**+ LH-global**
5	Bedson & Turnbull (2002)	*N* = 15 / 27 years	Behavioural	Letters	NR	NR	13–17	Bilateral	NR	150ms	Divided	Go/No-go	Accuracy	+ RH-global	—
			Behavioural	Objects	NR	NR	13–17	Bilateral	NR	150ms	Divided	Go/No-go	Accuracy	+ RH-global	—
6	Kéïta & Bedoin (2011)	*N* = 32 / 22.7 years	Behavioural	Letters	3.80°×4.00°	0.35°×0.40°	16–26	Unilateral	2.00°	175ms	Divided	Forced choice	RT/ Accuracy	RT: + RH-global Accuracy: —	RT: — Accuracy: + LH-local
		N = 32 / 22.5 years	Behavioural	Objects	3.80°×4.00°	0.35°×0.40°	24–32	Unilateral	2.00°	175ms	Divided	Forced choice	RT/ Accuracy	RT: — Accuracy: **+ RH-local**	RT: — Accuracy: **+ LH-global**
7	Brederoo et al. (2017)	*N* = 17 / 19.5 years	Behavioural	Letters	3.50°×3.50°	0.49°×0.49°	7–13	Unilateral/ Bilateral	0.50°	120ms	Divided	Forced choice	Accuracy	+ RH-global	+ LH-local
			Behavioural	Objects	3.50°×3.50°	0.49°×0.49°	8–12	Unilateral/ Bilateral	0.50°	120ms	Divided	Forced choice	Accuracy	+ RH-global	+ LH-local
8	Present Study (2024)	*N* = 27 / 20.59 years	Behavioural	Letters	2.30°× 3.08°	0.40°×0.50°	7–10	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ Accuracy	RT: + RH-global Accuracy: —	RT: + LH-local Accuracy: —
			Behavioural	Objects	3.30°× 3.30°	0.50°×0.50°	10–15	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ Accuracy	RT, accuracy: + RH-global	RT, accuracy: + LH-local
			Behavioural	Shapes	3.30°× 3.30°	0.50°×0.50°	10–15	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ Accuracy	—	RT: — Accuracy: + LH-local

Note. The studies are listed in chronological order of publication year. ERP: event-related potentials; RBF: relative regional blood flow; NA: not applicable; NR: not reported; +: significant findings found for RH or LH specialisation; —: no significant findings found for RH or LH specialisation. RH-global: right hemisphere specialisation for global processing; LH-local: left hemisphere specialisation for local processing; RH-local: right hemisphere specialisation for local processing; LH-global: left hemisphere specialisation for global processing. [a] Martinez et al.'s (1997) mental-counting response mode for their neuroimaging task required participants to keep a mental count of the number of times the target appeared at the attended processing level (global level *or* local level).

2.1.2 Effects of Ageing

Ageing is related to changes in many aspects of visual attention, including global-local processing. Widely reported behavioural findings have revealed that older adults demonstrate a local-processing bias when compared to young adults. Specifically, older adults demonstrate faster RT or higher accuracy in detecting stimuli at the local level relative to the global level, both for centrally-presented stimuli (Insch et al., 2012; Lux et al., 2008; Slavin et al., 2002) and for unilaterally-presented stimuli (Oken et al., 1999).[1] The right-hemisphere ageing hypothesis (Albert, 1981; Brown & Jaffe, 1975; Klisz, 1978) has been put forth to explain this age-related local-processing bias. The main idea here is that the RH is more vulnerable to ageing than the LH, with LH functions remaining relatively stable across the lifespan (see Goldstein & Shelly, 1981). Additional support for the right-hemisphere ageing hypothesis includes the finding that older adults have a rightward attentional bias in the landmark task, with the right half of lines perceived as being longer than the left half of lines (Schmitz & Peigneux, 2011), and that older adults have greater difficulties with: visuospatial working memory compared to verbal working memory (Jenkins et al., 2000); low-spatial-frequency information compared to high-spatial-frequency information (Wang et al., 2019); and reorienting attention from invalid cues in the RVF to targets in the LVF in a spatial-cueing task (Guilbert et al., 2019).

There are four outstanding questions that require further investigation of the extent to which the right-hemisphere ageing hypothesis explains the local-processing bias found in older adults:

[1] For unilaterally-presented stimuli (i.e., stimuli presented either to the LVF or to the RVF), the local-processing bias for behavioural measures is calculated by comparing the participants' performance for processing global-level and local-level stimuli after collapsing (i.e., averaging) across visual field of presentation.

1. Why are there inconsistent findings for the local-processing bias in older adults, which also sometimes include findings for a global-processing bias?
2. Is the local-processing bias found in older adults driven by age-related changes in local processing or age-related changes in global processing?
3. If the local-processing bias in older adults is driven by age-related difficulties with global processing, can these difficulties be attributed to age-related changes in RH functioning?
4. Does stimulus category (letters, verbalisable objects, and nonverbalisable shapes) affect the local-processing bias?

To address the first question, the difference in the size and number of local-level stimuli in the hierarchical figures used in previous studies needs to be considered (see Table 2.2 for a summary). For example, a local-processing bias (i.e., local-level stimuli detected faster or more accurately than global-level stimuli) was found in older adults in the study by Oken et al. (1999), in which nine to 12 local-level stimuli were used in each hierarchical figure. In contrast, a global-processing bias (i.e., global-level stimuli detected faster or more accurately than local-level stimuli) was found in older adults in studies that used a larger number of local-level stimuli.[2]The global-processing bias was found in RT differences, by Agnew et al. (2016; 18 to 22 local-level stimuli), Georgiou-Karistianis et al. (2006; 14 to 22 local-level stimuli), and Roux and Ceccaldi (2001; 18 to 22 local-level stimuli), and in accuracy differences, by Bruyer et al. (2003; 11 to 17 local-level stimuli), and Roux and Ceccaldi (2001; 18 to 22 local-level stimuli). It has been posited that when a larger number of local-level stimuli are used to make up a hierarchical figure, the global-level stimulus becomes more perceptually salient than the local-level stimuli (see Yovel et al., 2001). Consequently, detection of the global-level stimulus may have been made easier in these studies, resulting in the finding of a global-processing bias in older adults.

[2] Bruyer and Scailquin (2000) found a global-processing bias for both RT and accuracy differences, but they did not report the number of local-level stimuli used in their hierarchical figures.

Table 2.2

Methodological Differences in Studies Examining the Effects of Ageing

	Study	Participants *N* / Age		Stimulus category	Stimulus size (degree)		Local-level density	Stimulus presentation	Eccentricity (° from fixation)	Presentation duration	Task type	Response mode	Dependent variable	Processing bias findings	
		Young	Older		Global size	Local size								Young	Older
1	Oken et al. (1999)	*N* = 20 / 23.4 years	*N* = 25 / 83.6 years	Objects	12.00°	1.00°-1.50°	9–12	Unilateral	8.00°	100ms	Focused	Go/No-go	RT	Equal	**Local**
													Accuracy	Equal	Equal
2	Bruyer & Scailquin (2000)	*N* = 16 / 19.25 years	*N* = 16 / 68.69 years	Letters	3.11°×3.11°	0.39°×0.39°	NR	Quadrants [a]	3.24°	50ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Global	Global
		N = 16 / 19.44 years	*N* = 21 / 69.37 years	Letters	3.11°×3.11°	0.39°×0.39°	NR	Quadrants [a]	3.24°	50ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Equal	Global
		N = 16 / 19.17 years	*N* = 21 / 72.60 years	Letters	3.11°×3.11°	0.39°×0.39°	NR	Quadrants [a]	3.24°	Young: 50ms Older: 200ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Global	Global
3	Roux & Ceccaldi (2001)	*N* = 16 / 22 years	*N* = 21 / 70 years	Letters	2.80°×4.00°	0.30°×0.50°	18–22	Quadrants [a]	2.80°	100ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Global	Global
4	Slavin et al. (2002)	*N* = 12 / 26.9 years	*N* = 12 / 75.8 years	Numbers	1.60°–3.55° ×6.75°	0.34°×0.57°	16–21	Central	NA	No limit	Focused	Forced choice	RT	Global	**Local**
													Accuracy	Global	NR
5	Bruyer et al. (2003)	*N* = 16 / 21.25 years	*N* = 16 / 70.69 years	Letters	3.11°×3.11°	0.39°×0.39°	11–17	Quadrants [a]	3.24°	50ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Global	Global
		N = 16 / 20.19 years	*N* = 16 / 69.44 years	Letters	3.11°×3.11°	0.39°×0.39°	11–17	Quadrants [a]	3.24°	50ms	Focused	Forced choice	RT	Global	Global
													Accuracy	Global	Global
6	Georgiou-Karistianis et al. (2006)	*N* = 20 / 28.10 years	*N* = 20 / 70.35 years	Numbers	1.24°–2.86° ×5.33°	0.19°-0.28° ×0.38°	14–22	Central	NA	No limit	Focused	Forced choice	RT	Global	Global
													Accuracy	Equal	Equal
7	Lux et al. (2008)	*N* = 22 / 21.7 years	*N* = 22 / 58.4 years	Letters	5.70°×8.50°	0.80°×1.00°	5×7	Central	NA	150ms	Focused	Forced choice	RT	Equal	**Local**
													Accuracy	Equal	Equal
				Letters	5.70°×8.50°	0.80°×1.00°	5×7	Central	NA	150ms	Divided	Forced choice	RT	Equal	**Local**
													Accuracy	Equal	**Local**

	Study	Participants *N* / Age		Stimulus category	Stimulus size (degree)		Local-level density	Stimulus presentation	Eccentricity (° from fixation)	Presentation duration	Task type	Response mode	Dependent variable	Processing bias findings	
		Young	Older		Global size	Local size								Young	Older
8	Staudinger et al. (2011)	*N* = 20 / 22.1 years	*N* = 20 / 57.0 years	Letters	5.70°×8.50°	0.80°×1.00°	3×5, 4×6, 5×7, 6×8,7×9	Central	NA	150ms	Focused	Forced choice	RT	Global	Equal
													Accuracy	Global	Global
9	Insch et al. (2012)	*N* = 52 / 25.81 years	*N* = 34 / 73.56 years	Objects	8.00°	0.75°	NR	Central	NA	NR	Focused	Forced choice	Accuracy	Equal	**Local**
10	Agnew et al. (2016)	*N* = 17 / 19.9 years	*N* = 15 / 65.4 years	Letters	3.00°×4.00°	0.30°×0.50°	18–22	Central	NA	No limit	Focused	Forced choice	RT	Global	Global
													Accuracy	Local	**Local**
11	Lithfous et al. (2016)	*N* = 22 / 24.43 years	*N* = 22 / 69.14 years	Letters	Sparse: 13.00°×13.00° Dense: 4.50°×4.50°	Sparse: NR Dense: NR	Sparse: 12–13 Dense: 49	Central	NA	100ms	Focused	Forced choice	RT	Sparse: Equal Dense: Global	Sparse: Equal Dense: Equal
													Accuracy	Sparse: Equal Dense: Global	Sparse: **Local** Dense: Equal
12	Present Study (2024)	*N* = 27 / 20.59 years	*N* = 34 / 72.23 years	Letters	2.30°× 3.08°	0.40°×0.50°	7–10	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ accuracy	RT: Local Accuracy: Equal	RT, accuracy: **Local**
		N = 27 / 20.59 years	*N* = 32 / 71.24 years	Objects	3.30°× 3.30°	0.50°×0.50°	10–15	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ accuracy	RT: Equal Accuracy: Equal	RT, accuracy: **Local**
		N = 27 / 20.59 years	*N* = 30 / 70.94 years	Shapes	3.30°× 3.30°	0.50°×0.50°	10–15	Unilateral	0.50°	150ms	Divided	Go/No-go	RT/ accuracy	RT: Equal Accuracy: Equal	RT, accuracy: **Local**

Note. The studies are listed in chronological order of publication year. NA: not applicable; NR: not reported; Local: a local-processing bias (i.e., significantly faster RT or higher accuracy for detecting local-level stimuli compared to global-level stimuli); Global: a global-processing bias (i.e., significantly faster RT or higher accuracy for detecting global-level stimuli compared to local-level stimuli); —: no significant findings for a local-processing bias in older participants; Equal: equal salience (i.e., no significant RT or accuracy differences in detecting global-level stimuli and local-level stimuli); Bold highlighting indicates the research findings for a local-processing bias in older adults.

[a] Bruyer and Scailquin (2000), Roux and Ceccaldi (2001), and Bruyer et al. (2003) presented their stimuli in quadrants (i.e., stimuli were presented in one of the four quadrants around central fixation—upper LVF, lower LVF, upper RVF, lower LVF).

To address the second question, a between-group comparison needs to be incorporated into the statistical analysis of the findings. The local-processing bias in older adults reported in previous studies was found by comparing the performance of older adults for global-level stimuli with that for local-level stimuli (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002). However, these studies did not report the performance differences in global-local processing for older adults compared to young adults. Consequently, the question remains as to whether the observed local-processing bias stemmed from older adults demonstrating better performance in detecting local-level stimuli compared to young adults, or from older adults demonstrating worse performance in detecting global-level stimuli compared to young adults.

To address the third question, a divided visual field presentation needs to be incorporated into the experiment design. Although some studies have reported evidence for a local-processing bias in the behavioural data (RT and accuracy) of older adults (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002), only Oken et al. presented stimuli unilaterally (i.e., presented stimuli either to the LVF or to the RVF) in a divided visual field presentation. Other studies have presented stimuli centrally, which is considered not to be an effective way to examine directly the effects of ageing on RH functioning and LH functioning (see Bourne, 2006 for a review of using a divided visual field presentation to examine hemispheric asymmetry). Consequently, although these studies reported a local-processing bias in older adults, it is unclear whether this can be attributed to age-related changes in RH functioning. To the best of our knowledge, there are only four studies in the literature (Bruyer et al., 2003; Bruyer & Scailquin, 2000; Oken et al., 1999; Roux & Ceccaldi, 2001) that have adopted a divided visual field presentation in older adults. Of these four studies, only Oken et al. reported findings in regard to hemispheric asymmetry. Contrary to the right-hemisphere ageing hypothesis, Oken et al.'s RT results for older participants did not demonstrate age-related difficulties in overall performance in the LVF/RH compared to the RVF/LH (regardless of global-local processing level). Importantly, in addition to finding hemispheric asymmetry (i.e., global-level verbalisable objects detected faster in the LVF/RH compared to the RVF/LH, and local-level verbalisable objects detected faster in the RVF/LH compared to the LVF/RH),

Oken et al. also reported a local-processing bias—older participants detected local-level verbalisable objects faster than global-level verbalisable objects (regardless of visual field of presentation). One potential confounding factor in the Oken et al. findings of hemispheric asymmetry remains to be investigated, which is that their stimuli were presented at a large eccentricity of 8.00° from central fixation. It has been suggested that the RH is specialised for stimuli of low visual acuity (Christman, 1989; Sergent, 1983). Since visual acuity decreases as eccentricity increases from central fixation (Lindell & Nicholls, 2003), low visual acuity at this eccentricity may have inadvertently enhanced RH functioning, resulting in the intact overall performance in the LVF/RH observed in Oken et al.'s older participants.

To address the fourth question, a within-subjects comparison with more than one stimulus category needs to be incorporated into the experiment design. The local-processing bias found in previous studies was based on participants tested with only one stimulus category, without a within-subjects comparison to other stimulus categories (e.g., letters only by Lux et al., 2008; numbers only by Slavin et al., 2002; verbalisable objects only by Oken et al., 1999). The question that arises is whether older adults will demonstrate the local-processing bias for stimulus categories when there are different demands for verbal *versus* visuospatial processing.

2.1.3 The Present Study

In the present study, we used a divided-attention paradigm, in which participants attended to both processing levels (i.e., global level and local level) at the same time, and a divided visual field presentation, in which hierarchical figures were presented unilaterally (i.e., presented either to the LVF or to the RVF) in a within-subjects experiment design. The stimuli were Navon's (1977) hierarchical figures, and there were three stimulus categories: hierarchical letters (verbalisable), hierarchical objects (verbalisable), and hierarchical shapes (nonverbalisable). The hierarchical letters were composed of letters (e.g., the letter, S), which were meant to be strictly processed by their verbal labels. The hierarchical objects were composed of familiar figures (e.g., ♡; heart), to which verbal labels could easily be applied. The hierarchical shapes were composed

of unfamiliar shape patterns (e.g.,), to which verbal labels could not easily be applied. All stimuli were presented at an eccentricity of 0.50° from central fixation.

This experiment setup allowed us to investigate two competing accounts of hemispheric asymmetry in global-local processing—the stimulus-independent account and the stimulus-dependent account. We aimed to examine systematically the effects of three different stimulus categories (letters, verbalisable objects, and nonverbalisable shapes) on hemispheric asymmetry for global-local processing in both young and older participants. Previous studies examining the effects of stimulus category on hemispheric asymmetry for global-local processing in young adults have only compared the findings for letter stimuli with those for verbalisable objects (e.g., Brederoo et al., 2017; Fink, Marshall, et al., 1997; Kéïta & Bedoin, 2011). No study thus far has explored the stimulus category of nonverbalisable shapes and compared these findings with those for letters or verbalisable objects in a within-subjects design.

This experiment setup also allowed us to investigate the extent to which the right-hemisphere ageing hypothesis (i.e., the RH is more vulnerable to ageing than the LH) can explain previous findings of a local-processing bias in older adults. The four outstanding questions listed above were taken into account by: (1) setting the size of the hierarchical figure and the number of local-level stimuli to match closely with what Yovel et al. (2001) recommended for an equal salience design; (2) including a between-group comparison in the statistical analysis, thus for the first time providing a comparison of older adults' performance for global processing and for local processing with that of young adults; (3a) using a divided visual field presentation, which is considered the best method for comparing left visual field/right-hemisphere performance with right visual field/left-hemisphere performance; (3b) using a small eccentricity of 0.50° from central fixation for unilateral stimulus presentation, as suggested by Yovel et al.; (4) conducting a within-subjects experiment including three stimulus categories, given that the age-related local-processing bias found in previous studies was based on participants tested with only one stimulus category.

2.2 Method

2.2.1 Participants

A total of 63 participants were recruited for this study: 27 young participants were recruited from the student population at the Australian National University, and 36 older participants were recruited from the University of the Third Age and the broader community in Canberra. All participants self-reported being of European descent, and living in Australia. Participants were excluded from the statistical analyses if they did not meet the following five inclusion criteria:

1. Right-handed, based on the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were considered to be right-handed if their laterality scores were higher than +50. One older participant scored lower than this laterality score cut-off and was excluded from all of the statistical analyses.
2. Normal or corrected-to-normal vision, as indicated by in-laboratory testing with a Snellen chart (Snellen, 1868). No young or older participants were excluded.
3. No history of self-reported neurological impairments. No young or older participants were excluded.
4. No evidence of cognitive impairment, as assessed by the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), with a score of 24 or greater indicating intact cognitive functioning (see Pugh et al., 2018; Thomann et al., 2020). One older participant scored lower than this MoCA cut-off score of 24 and was excluded from all of the statistical analyses.
5. High overall accuracy on *target-absent trials* (i.e., the hierarchical figures in which no target was presented, and therefore no response was required). A response to a target-absent trial indicated that the participant either did not discriminate targets from distractors or tended to respond quickly but with low accuracy. Different accuracy cut-offs were adopted based on the relative overall accuracy for the target-absent trials for the three stimulus categories (letters: 80% or greater; verbalisable objects: 70% or greater; and nonverbalisable shapes: 60% or

greater). Two older participants, who did not meet the accuracy cut-off, were excluded from the statistical analyses for verbalisable objects and nonverbalisable shapes (but not from the analyses for letters), and two older participants, who did not meet the accuracy cut-off, were excluded from the statistical analyses for nonverbalisable shapes (but not from the analyses for letters or verbalisable objects).

In summary, of the 63 participants recruited for the present study, 27 young participants were included in all of the statistical analyses, and two older participants were excluded from all of the statistical analyses. The final statistical analyses included a sample of 27 young participants and 34 older participants. Of these 34 older participants, four were excluded from some but not all of the statistical analyses. See Table 2.3 for full details. The power analysis conducted using G*Power (version 3.1) indicated that to achieve 85% power with $\alpha = .05$, a minimal sample size of 23 young participants and 29 older participants was required.[3] All participants provided written informed consent prior to participation in the study and received monetary compensation (or course credit for eligible young participants). The study was approved by the Australian National University Human Research Ethics Committee (Protocol: 2019/795).

[3] The main research question concerned hemispheric asymmetry, and thus the power analysis was based on the RT effect size for the Level (global, local) × Visual Field (LVF, RVF) interaction for each of the two age groups. In young participants, an effect size of $\eta_p^2 = .40$ was adopted based on the findings from Yovel et al. (2001; see p. 1381), who had an effect size of $\eta_p^2 = .59$ for letters, and from Martinez et al. (1997; see p. 1688), who had an effect size of $\eta_p^2 = .40$ for nonverbalisable shapes (as retrieved from the F statistics they reported). We opted for the smaller effect size of $\eta_p^2 = .40$ from Martinez et al., as it required a larger minimum sample size to achieve the same level of power compared to the larger effect size of $\eta_p^2 = .59$ from Yovel et al. In older participants, the effect size of $\eta_p^2 = .28$ was adopted based on the effect size retrieved from the F statistics reported by Oken et al. (1999; see p. 79), which was the only previous study examining hemispheric asymmetry in older adults using verbalisable objects.

Table 2.3

Demographic Information and Target-Absent Trial Accuracy for the Young and Older Participants Included in the Data Analysis for Each of Three Stimulus Categories (Letters, Verbalisable Objects, Nonverbalisable Shapes)

	Letters		Verbalisable Objects		Nonverbalisable Shapes	
	Young	Older	Young	Older	Young	Older
N	27	34	27	32	27	30
Female (*n*)	16	26	16	24	16	22
%	59.26%	74.28%	59.26%	72.83%	59.26%	70.97%
Age						
M	20.59	72.23	20.59	71.24	20.59	70.94
SD	2.45	8.02	2.45	7.98	2.45	8.08
Range	19–30	55–88	19–30	55–88	19–30	55–88
Target-absent trials accuracy	97.24%	94.03%	96.18%	87.34%	96.30%	83.23%

2.2.2 Apparatus and Stimuli

Experiments were programmed in Inquisit (version 6.2.1) and were presented on a 27-inch Dell S2719DGF monitor with a 60 Hz refresh rate and 2560 × 1440 pixels resolution. Participants' RT and accuracy were recorded with a Cedrus RB-844 response pad. A forehead-and-chin rest was used to maintain a 57 cm constant eye-to-screen viewing distance for each participant.

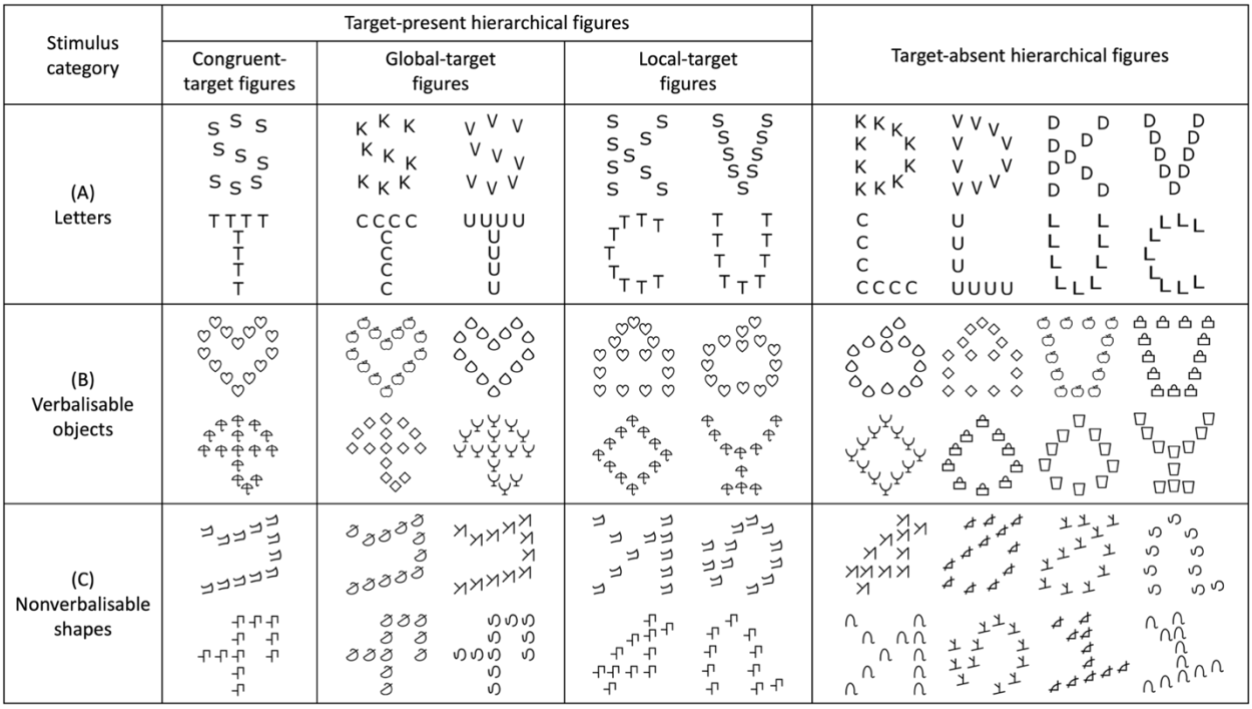
The present study consisted of three experiments with hierarchical figures: hierarchical letters, hierarchical objects, and hierarchical shapes. The hierarchical letters were large global letters (size = 2.30° × 3.08°) composed of seven to 10 small local letters (size = 0.40° × 0.50°). The global and local size of the hierarchical letters was based on the equal salience experiment design reported by Yovel et al. (2001). The hierarchical objects were large global verbalisable objects (size = 3.30° × 3.30°) composed of 10 to 15 small local verbalisable objects (size = 0.50° × 0.50°). The hierarchical shapes were large global nonverbalisable shapes (size = 3.30° × 3.30°) composed of 10 to 15 small local nonverbalisable shapes (size = 0.50° × 0.50°). Although the structure of the verbalisable objects and nonverbalisable shapes was of the same visual complexity, both the verbalisable objects and the nonverbalisable shapes were visually more complex than the letters. Therefore, to achieve equal discriminability with the hierarchical letters at

both the global and the local level, more local stimuli (i.e., 10 to 15 local stimuli for objects and shapes as compared to 7 to 10 local stimuli for letters) were used to make up the hierarchical verbalisable objects and the hierarchical nonverbalisable shapes. The average centre-to-centre distance between each pair of consecutive local stimuli for hierarchical letters was 0.73° (range: 0.60°–0.84°), for hierarchical verbalisable objects was 0.68° (range: 0.60°–0.80°), and for hierarchical nonverbalisable shapes was 0.73° (range: 0.66°–0.88°).

For each of the three stimulus categories tested (letters, verbalisable objects, and nonverbalisable shapes), there were two targets and six distractors. The target letters were "S" and "T". The target verbalisable objects were (heart) and (umbrella). The target nonverbalisable shapes were and . All of the other letters, verbalisable objects, and nonverbalisable shapes were distractors. Within a hierarchical figure, targets were either present (target-present hierarchical figures) or absent (target-absent hierarchical figures). There were three types of target-present hierarchical figures: congruent-target figures (the same target appeared at both the global and local level); global-target figures (one target appeared at the global level and one distractor appeared at the local level); and local-target figures (one target appeared at the local level and one distractor appeared at the global level). There was only one type of target-absent hierarchical figure, which was made up of two different distractors (one distractor appeared at the global level and one distractor appeared at the local level). There were 18 hierarchical figures for each of the three stimulus categories (18 hierarchical letters, 18 hierarchical verbalisable objects, 18 hierarchical nonverbalisable shapes), and for each stimulus category, there were two congruent-target figures, four global-target figures, four local-target figures, and eight target-absent figures. See Figure 2.1 for full details.

Figure 2.1

Hierarchical Figures for Three Experiments: Hierarchical Letters, Hierarchical Verbalisable Objects, and Hierarchical Nonverbalisable Shapes



Note. Panel (A) hierarchical-letters experiment: target letters were S and T, and distractor letters were D, C, K, L, U, and V. Panel (B) hierarchical verbalisable objects experiment: target objects were ♡ (heart) and ☂ (umbrella), and distractor objects were (apple), (briefcase), (cup), ◇ (diamond), (drop), and (glass). Panel (C) hierarchical nonverbalisable shapes experiment: target shapes were and , and distractor shapes were , , , , , and .

The hierarchical figures were presented in black against a white background. For each trial, one hierarchical figure was presented unilaterally either to the LVF or to the RVF. The medial edge of the hierarchical figure was positioned 0.50° to the left or to the right of a central fixation cross (size = 0.40° × 0.40°).[4] To prevent afterimages, two post-stimulus masks were presented (bilaterally) immediately after the presentation of a hierarchical figure. The medial edges of each of the post-stimulus masks were positioned

[4] The eccentricity of 0.50° for the presentation of the hierarchical figures was based on the study by Yovel et al. (2001). Visual acuity decreases as eccentricity increases from central fixation (Lindell & Nicholls, 2003), and the RH is specialised for processing stimuli with low visual acuity (Christman, 1989; Sergent, 1983). Yovel et al. suggested that stimuli with low visual acuity due to a large eccentricity may inadvertently enhance RH activity, introducing a bias in hemispheric asymmetry for global-local processing.

0.50° to the left or to the right of the central fixation cross. The post-stimulus mask comprised Gaussian white noise (300 pixels × 300 pixels), made up of noise elements with a Gaussian mean of 0 and standard deviation of 1. There were two sizes for the post-stimulus masks: 2.30° × 3.08° for hierarchical letters; 3.30° × 3.30° for hierarchical verbalisable objects and nonverbalisable shapes.

2.2.3 Procedure

Participants were tested individually in a distraction-free room. To reduce the likelihood that participants would adopt verbal strategies for processing the verbalisable objects and nonverbalisable shapes, the order of the three experiments was not randomised. [5] Given that nonverbalisable shapes were meant to be processed visuospatially, the hierarchical nonverbalisable shapes experiment was conducted first, followed by the hierarchical verbalisable objects experiment. The hierarchical-letters experiment was conducted last since letters were expected to be processed verbally. At the beginning of each of the three experiments (letters, verbalisable objects, and nonverbalisable shapes), participants were first shown all of the hierarchical figures to be used in that specific experiment, and then they performed two practice blocks to ensure both understanding and compliance with the task instructions for the experiment block. Feedback regarding accuracy was provided only in the practice blocks.

The experiment block for each of the three experiments (letters, verbalisable objects, and nonverbalisable shapes) consisted of 160 trials, presented in a random order. Of the 160 trials, 96 were target-present trials (consisting of 32 congruent-target trials, 32 global-target trials, and 32 local-target trials) and 64 were target-absent trials.

[5] To ensure that experiment order would not influence overall performance on nonverbalisable shapes and verbalisable objects, we conducted a pilot study with 18 young participants, who self-reported being of European descent: 10 participants performed the nonverbalisable shapes experiment first and the verbalisable objects experiment second; 8 participants performed the verbalisable objects experiment first and the nonverbalisable shapes experiment second. Our RT data revealed a significant main effect for Stimulus Category (nonverbalisable shapes, verbalisable objects), $\chi^2(1) = 261.98$, $p < .001$), but there was no significant main effect for Experiment Order (Order 1, Order 2), $p = .11$ nor was there a significant effect for the Stimulus Category × Experiment Order interaction, $p = .23$. The significant main effect of stimulus category indicated that, regardless of experiment order, participants were significantly slower at detecting nonverbalisable shapes (668.70 ms) compared to verbalisable objects (587.23 ms).

Hierarchical figures were randomly presented either to the LVF or to the RVF in equal proportion: in 50% of trials, the hierarchical figures were presented to the LVF and in the remaining 50% of trials, the hierarchical figures were presented to the RVF. A divided-attention paradigm was adopted, in which participants were instructed to attend to both the global level and the local level simultaneously. A divided-attention paradigm has been suggested to produce a greater effect size for hemispheric asymmetry for global-local processing (Yovel et al., 2001). Participants were instructed to respond as quickly and as accurately as possible, by pressing a green-coloured button on the Cedrus response pad with their right index finger, when they saw a target appear at either the global level or the local level. They were instructed not to respond when a target did not appear at either the global level or the local level. Each trial began with a central fixation cross (500 ms), followed by a hierarchical figure presented unilaterally either to the LVF or to the RVF (150 ms), and then two post-stimulus masks were presented bilaterally (1000 ms) before the inter-trial interval (1000 ms). No feedback was provided in the experiment trials. The presentation duration of 150 ms for the hierarchical figures was chosen because a short stimulus duration prevents eye movements away from central fixation and towards the stimulus. For this reason, previous researchers (Blanca et al., 1994; Bourne, 2006; Hunter & Brysbaert, 2008) have recommended a presentation duration range of between 50 ms and 180 ms, but no less than 50 ms because too short a presentation duration decreases visual acuity and can lead to enhanced RH activity (Boles & Karner, 1996; Evert & Kmen, 2003).

2.2.4 Statistical Analysis Plan

Both RT and accuracy were analysed.[6] For RT, gamma mixed-effects regression was adopted, which used RT data by trials instead of mean RT. The gamma distribution is positively skewed by nature and takes values between [0, +∞], which is better suited for

[6] Reporting both RT and accuracy allowed for direct comparisons to be made between our findings and previous research on ageing and global-local processing. The majority of studies we have cited examining ageing and global-local processing have reported both RT and accuracy analyses (see Agnew et al., 2016; Bruyer et al., 2003; Bruyer & Scailquin, 2000; Georgiou-Karistianis et al., 2006; Lithfous et al., 2016; Lux et al., 2008; Oken et al., 1999; Roux & Ceccaldi, 2001; Slavin et al., 2002; Staudinger et al., 2011).

capturing the properties of RT (see Lo & Andrews, 2015). For accuracy, logistic mixed-effects regression was adopted, which used accuracy data by trials (i.e., correct, incorrect) instead of mean accuracy (i.e., proportion of correct responses).

An omnibus analysis was conducted. The fixed effects included three within-subjects predictors: Level (global, local), Visual Field (LVF, RVF), and Stimulus Category (letters, verbalisable objects, and nonverbalisable shapes), and one between-subjects predictor: Age Group (young, older). First, the omnibus analysis explored the main effects and interactions for all four fixed effects. Second, the omnibus analysis examined overall performance differences for the three stimulus categories in young and older participants; these differences would be indicated by a significant Stimulus Category × Age Group interaction.

Three follow-up analyses were conducted for each of the three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes). The fixed effects included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF), and one between-subjects predictor: Age Group (young, older). The first aim of these follow-up analyses was to examine the research question regarding hemispheric asymmetry for global-local processing. Specifically, these follow-up analyses examined age-group differences in hemispheric asymmetry for global-local processing for each of the three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes). Hemispheric asymmetry for global-local processing would be indicated by two contrasts in the post hoc pairwise comparisons for a significant Level × Visual Field interaction. RH-global specialisation would be indicated by significantly better performance in detecting global-level stimuli presented in the LVF/RH compared to the RVF/LH, and LH-local specialisation would be indicated by significantly better performance in detecting local-level stimuli presented in the RVF/LH compared to the LVF/RH (Brederoo et al., 2017; Hübner, 1998; Martin, 1979; Sergent, 1982; Van Kleeck, 1989; Yovel et al., 2001). Significant three-way interactions for Level (global, local) × Visual Field (LVF, RVF) × Age Group (young, older) were followed up with additional analyses within each of the two age groups (young, older). The fixed effects included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF). The second aim of these follow-up

analyses was to examine the research question regarding the age-related local-processing bias in older participants, which would be indicated by a significant two-way interaction for Level (global, local) × Age Group (young, older). For all analyses, the dependent variable was RT for correct trials or accuracy for all trials, for each participant.

Participants were entered as random intercepts for all analyses. While it has been recommended that all within-subjects factors be included as random slopes to capture dependencies in the repeated-measures design (Barr, 2013), we did not include all within-subjects factors in some of the analyses to avoid over-fitting due to singular fits (i.e., the random slopes were too complex to be supported by the data). For the omnibus analysis, Level (global, local), Visual Field (LVF, RVF), and Stimulus Category (letters, verbalisable objects, and nonverbalisable shapes) were entered into the random slopes for accuracy, while only Level (global, local) and Visual Field (LVF, RVF) were entered into the random slopes for RT. For the follow-up analyses examining hemispheric asymmetry and the age-related local-processing bias in each of the three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes), Level (global, local) and Visual Field (LVF, RVF) were entered into the random slopes for RT, while only Level (global, local) was entered into the random slopes for accuracy. For the additional analyses examining hemispheric asymmetry within each of the two age groups (young, older), only Level (global, local) was entered into the random slopes for RT and accuracy to avoid over-fitting due to singular fits. All analyses were carried out in R (version 4.0.5), and all the fixed effects were deviation-coded. The gamma mixed-effects regression with the identity link function and the logistic mixed-effects regression with the logit link function was conducted using the "glmer" function in the "lme4" package. The Type-III analyses of variance (ANOVA) tables with Wald chi-squares tests were obtained using the "Anova" function in the "car" package. Post hoc pairwise comparisons with Tukey-corrected *p* values were conducted using the "emmeans" function in the "emmeans" package. Estimated marginal means and standard errors were obtained using the "effect" function in the "effects" package. Post hoc pairwise comparisons report the mean difference (MD) in milliseconds for the RT data and the MD in log-odds-ratio scale for the accuracy data. Effect size *d* was computed for post hoc pairwise comparisons by dividing MD by the

square root of the sum of variance for random intercepts, random slopes, and residuals (Westfall et al., 2014; also see Brysbaert & Stevens, 2018).[7]

2.3 Results

2.3.1 Omnibus Analysis

The omnibus analysis indicated there were significant three-way and/or four-way interactions with Stimulus Category (letters, verbalisable objects, and nonverbalisable shapes) for RT and accuracy (see Table 2.4 for the main effects and interactions for RT and accuracy in the omnibus analysis). As planned, three follow-up analyses for each of the three stimulus categories were conducted to investigate the two main research questions regarding hemispheric asymmetry for global-local processing and the age-related local-processing bias.

Table 2.4

Main Effects and Interactions of the Omnibus Analysis for Reaction Time and Accuracy

Effects	RT			Accuracy		
	χ^2	*df*	*p*	χ^2	*df*	*p*
Level	194.42	1	< .001***	7.46	1	.006**
Visual Field	1.61	1	.20	.003	1	.96
Stimulus Category	870.95	2	< .001***	97.25	2	< .001***
Age Group	162.58	1	< .001***	66.60	1	< .001***
Level × Visual Field	104.44	1	< .001***	18.67	1	< .001***
Level × Stimulus Category	601.16	2	< .001***	2.54	2	.28
Level × Age Group	620.58	1	< .001***	36.68	1	< .001***
Visual Field × Stimulus Category	1.69	2	.43	1.67	2	.43
Visual Field × Age Group	.85	1	.36	.07	1	.79
Stimulus Category × Age Group	953.23	2	< .001***	11.62	2	.003**
Level × Visual Field × Stimulus Category	67.51	2	< .001***	5.31	2	.07
Level × Visual Field × Age Group	52.94	1	< .001***	6.18	1	.01*
Level × Stimulus Category × Age Group	467.53	2	< .001***	17.46	2	< .001***
Visual Field × Stimulus Category × Age Group	33.66	2	< .001***	.59	2	.74
Level × Visual Field × Stimulus Category × Age Group	116.81	2	< .001***	1.96	2	.38

Note. *** $p < .001$; ** $p < .01$; * $p < .05$.

[7] To the best of our knowledge, there is currently no published study or R package available for computing effect size in generalised mixed-effects models (e.g., gamma and logistic mixed-effects models) with an ANOVA-style interpretation (i.e., main effects, interaction effects, and post hoc pairwise comparisons). The effect size *d* reported in this study was designed for calculating the effect size of regression coefficients in linear mixed-effects models (Brysbaert & Stevens, 2018; Westfall et al., 2014).

The overall performance for the three stimulus categories in young and older participants indicated there was a significant Stimulus Category × Age Group interaction, both for RT and accuracy. Post hoc pairwise comparisons for RT indicated that: (1) young participants detected letters faster than verbalisable objects and nonverbalisable shapes, and they detected verbalisable objects faster than nonverbalisable shapes (young participants: letters = 490.21 ms, SE = 3.55; verbalisable objects = 542.68 ms, SE = 3.94; nonverbalisable shapes = 600.75 ms, SE = 3.98; $MD_{L–VO}$ = −51.70 ms, 95% CI [−59.23, −44.18], z = −19.69, p < .001, d = 1.16; $MD_{L–NVS}$ = −109.66 ms, 95% CI [−119.95, −99.37], z = −30.38, p < .001, d = 2.46; $MD_{VO–NVS}$ = −57.96 ms, 95% CI [−67.84, −48.07], z = −16.71, p < .001, d = 1.30); (2) older participants detected letters faster than verbalisable objects and nonverbalisable shapes, but there were no RT differences in the detection of verbalisable objects and nonverbalisable shapes (older participants: letters = 568.96 ms, SE = 3.63; verbalisable objects = 586.21 ms, SE = 3.82; nonverbalisable shapes = 587.07 ms, SE = 3.58; $MD_{L–VO}$ = −15.09 ms, 95% CI [−23.09, −7.09], z = −5.38, p < .001, d = 0.34; $MD_{L–NVS}$ = −15.67 ms, 95% CI [−24.06, −7.27], z = −5.32, p < .001, d = 0.34; $MD_{VO–NVS}$ = −0.58 ms, 95% CI [−10.46, 9.31], z = −0.17, p = .99, d = 0.013). Post hoc pairwise comparisons for accuracy indicated that: (1) young participants detected letters more accurately than verbalisable objects and nonverbalisable shapes, and they detected verbalisable objects more accurately than nonverbalisable shapes (young participants: letters = .9970, SE = .0014; verbalisable objects = .9860, SE = .0036; nonverbalisable shapes = .9420, SE = .0115; $MD_{L–VO}$ = 1.54, 95% CI [0.29, 2.80], z = 3.50, p = .006, d = 0.88; $MD_{L–NVS}$ = 3.01, 95% CI [1.67, 4.36], z = 6.39, p < .001, d = 1.71; $MD_{VO–NVS}$ = 1.47, 95% CI [0.71, 2.23], z = 5.50, p < .001, d = 0.84); (2) older participants detected letters more accurately than verbalisable objects and nonverbalisable shapes, but there were no accuracy differences in the detection of verbalisable objects and nonverbalisable shapes (older participants: letters = .9717, SE = .0074; verbalisable objects = .8143, SE = .0257; nonverbalisable shapes = .7398, SE = .0340; $MD_{L–VO}$ = 2.06, 95% CI [1.44, 2.67], z = 9.53, p < .001, d = 1.17; $MD_{L–NVS}$ = 2.49, 95% CI [1.68, 3.30], z = 8.75, p < .001, d = 1.42; $MD_{VO–NVS}$ = 0.43, 95% CI [−0.05, 0.91], z = 2.58, p = .10, d = 0.24).

2.3.2 Letters

For the stimulus category of letters, there were similar results overall for RT and accuracy. For RT, there were significant main effects of Level, $\chi^2(1) = 195.78$, $p < .001$, and Age Group, $\chi^2(1) = 95.88$, $p < .001$, but there was no significant main effect of Visual Field ($p = .43$). For accuracy, there was a significant main effect of Age Group, $\chi^2(1) = 8.93$, $p = .003$, but there was no significant main effect of Level ($p = .96$) or Visual Field ($p = .80$). Results for all interaction effects relevant to the two research questions for the category of letters are presented below.

2.3.2.1 Right-Left Hemisphere Asymmetry for Global-Local Processing in Letters. For RT, there was a significant Level × Visual Field interaction, $\chi^2(1) = 68.92$, $p < .001$, but there was no significant Visual Field × Age Group interaction ($p = .72$) nor was there a Level × Visual Field × Age Group interaction ($p = .56$). These results indicated that although there were RT differences in detecting global and local letters in the LVF/RH and RVF/LH, there were no age-group differences in hemispheric asymmetry. Post hoc pairwise comparisons for the Level × Visual Field interaction provided RT evidence for RH specialisation for global processing and LH specialisation for local processing in both young and older participants: global letters were detected faster in the LVF/RH than in the RVF/LH (global: $MD_{LVF/RH–RVF/LH} = −17.80$ ms, 95% CI [−30.80, −4.80], $z = −3.52$, $p = .003$, $d = 0.31$), and local letters were detected faster in the RVF/LH than in the LVF/RH (local: $MD_{LVF/RH–RVF/LH} = 24.40$ ms, 95% CI [12.40, 36.50], $z = 5.21$, $p < .001$, $d = 0.43$). See Figure 2.2A right panel.

For accuracy, there was a significant Level × Visual Field interaction, $\chi^2(1) = 5.03$, $p = .02$, but there was no significant Visual Field × Age Group interaction ($p = .60$) or Level × Visual Field × Age Group interaction ($p = .09$). None of the post hoc pairwise comparisons for the Level × Visual Field interaction in young and older participants reached significance (all ps ≥ .11). See Figure 2.3A right panel.

2.3.2.2 Age-Related Local-Processing Bias in Letters. For RT, there was a significant Level × Age Group interaction, $\chi^2(1) = 68.92$, $p < .001$. Post hoc pairwise comparisons indicated that: (1) both young participants and older participants were

faster in detecting local letters than global letters (young: $MD_{global–local}$ = 25.28 ms, 95% CI [8.48, 42.10], z = 3.87, p < .001, d = 0.44; older: $MD_{global–local}$ = 129.30 ms, 95% CI [112.25, 146.30], z = 19.48, p < .001, d = 2.27); (2) both global letters and local letters were detected faster by young participants than by older participants (global: $MD_{young–old}$ = −130.13 ms, 95% CI [−151.70, 108.59], z = −15.52, p < .001, d = 2.28; local: $MD_{young–old}$ = −26.11 ms, 95% CI [−49.50, −2.76], z = −2.87, p = .02, d = 0.46). See Figure 2.2A left panel.

For accuracy, there was a significant Level × Age Group interaction, $\chi^2(1) = 19.12$, p < .001. Post hoc pairwise comparisons indicated that: (1) young participants demonstrated no accuracy differences in detecting global and local letters (young: $MD_{global–local}$ = 1.97, 95% CI [−0.22, 4.19], z = 2.31, p = .09, d = 1.01), whereas older participants were more accurate in detecting local letters than global letters (older: $MD_{global–local}$ = −1.94, 95% CI [−3.14, −0.73], z = −4.14, p < .001, d = 1.00); (2) global letters were detected more accurately by young participants than by older participants (global: $MD_{young–old}$ = 4.05, 95% CI [2.06, 6.05], z = 5.21, p < .001, d = 2.08), but there were no accuracy differences between young and older participants in detecting local letters (local: $MD_{young–old}$ = 0.13, 95% CI [−1.07, 1.33], z = 0.28, p = .99, d = 0.067). See Figure 2.3A left panel.

2.3.3 Verbalisable Objects

For the stimulus category of verbalisable objects, there were similar results overall for RT and accuracy. For RT, there were significant main effects of Level, $\chi^2(1) = 9.17$, p = .002, and Age Group, $\chi^2(1) = 13.10$, p < .001, but there was no significant main effect of Visual Field (p = .70). For accuracy, there were significant main effects of Level, $\chi^2(1)$ = 10.94, p < .001, and Age Group, $\chi^2(1) = 59.91$, p < .001, but there was no significant main effect of Visual Field (p = .63). Results for all interaction effects relevant to the two research questions for the category of verbalisable objects are presented below.

2.3.3.1 Right-Left Hemisphere Asymmetry for Global-Local Processing in Verbalisable Objects. For RT, there was a significant Level × Visual Field interaction, $\chi^2(1)$ = 17.40, p < .001, and a significant Level × Visual Field × Age Group interaction, $\chi^2(1) = 10.89$, p < .001, but there was no significant Visual Field × Age Group interaction

(p = .54). These results indicated that although there were RT differences in detecting global and local verbalisable objects in the LVF/RH and RVF/LH, there were also age-group differences in hemispheric asymmetry. Planned additional analyses within each of the two age groups (young, older) were conducted to examine the significant Level × Visual Field × Age Group interaction. In young participants, there was a significant Level × Visual Field interaction, $\chi^2(1) = 30.54$, $p < .001$, whereas in older participants there was no significant Level × Visual Field interaction (p = .20). Post hoc pairwise comparisons for the Level × Visual Field interaction provided RT evidence for RH specialisation for global processing and LH specialisation for local processing in young participants only: global verbalisable objects were detected faster in the LVF/RH than in the RVF/LH (global: $MD_{LVF/RH–RVF/LH}$ = −20.34 ms, 95% CI [−37.94, −2.73], z = −2.97, p = .02, d = 0.39), and local verbalisable objects were detected faster in the RVF/LH than in the LVF/RH (local: $MD_{LVF/RH–RVF/LH}$ = 28.02 ms, 95% CI [11.21, 44.83], z = 4.28, $p < .001$, d = 0.54). See Figure 2.2B right panel.

For accuracy, there was a significant Level × Visual Field interaction, $\chi^2(1) = 14.08$, $p < .001$, but there was no significant Visual Field × Age Group interaction (p = .85) nor was there a Level × Visual Field × Age Group interaction (p = .55). These results indicated that although there were accuracy differences in detecting global and local verbalisable objects in the LVF/RH and RVF/LH there were no age-group differences in hemispheric asymmetry. Post hoc pairwise comparisons for the Level × Visual Field interaction provided accuracy evidence for RH specialisation for global processing and LH specialisation for local processing in both young and older participants: global verbalisable objects were detected more accurately in the LVF/RH than in RVF/LH (global: $MD_{LVF/RH–RVF/LH}$ = 0.62, 95% CI [0.04, 1.19], z = 2.75, p = .03, d = 0.37), and local verbalisable objects were detected more accurately in the RVF/LH than in the LVF/RH (local: $MD_{LVF/RH–RVF/LH}$ = −0.67, 95% CI [−1.34, −0.004], z = −2.58, p = .048, d = 0.40). See Figure 2.3B right panel.

2.3.3.2 Age-Related Local-Processing Bias in Verbalisable Objects. For RT, there was a significant Level × Age Group interaction, $\chi^2(1) = 23.23$, $p < .001$. Post hoc pairwise comparisons indicated that: (1) young participants demonstrated no RT differences in

detecting global and local verbalisable objects (young: $MD_{global–local}$ = 3.89 ms, 95% CI [−25.40, 33.20], z = 0.34, p = .97, d = 0.058), whereas older participants were faster in detecting local verbalisable objects than global verbalisable objects (older: $MD_{global–local}$ = 54.11 ms, 95% CI [27.50, 80.70], z = 5.22, p < .001, d = 0.81); (2) global verbalisable objects were detected faster by young participants than by older participants (global: $MD_{young–old}$ = −68.87 ms, 95% CI [−107.00, −30.70], z = −4.64, p < .001, d = 1.03), but there were no RT differences between young and older participants in detecting local verbalisable objects (local: $MD_{young–old}$ = −18.65 ms, 95% CI [−47.50, 10.20], z = −1.66, p = .35, d = 0.28). See Figure 2.2B left panel.

For accuracy, there was a significant Level × Age Group interaction, $\chi^2(1) = 4.60$, p = .03. Post hoc pairwise comparisons indicated that: (1) young participants demonstrated no accuracy differences in detecting global and local verbalisable objects (young: $MD_{global–local}$ = −0.35, 95% CI [−1.67, 0.98], z = −0.67, p = .91, d = 0.21), whereas older participants were more accurate in detecting local verbalisable objects than global verbalisable objects (older: $MD_{global–local}$ = −1.59, 95% CI [−2.35, 0.83], z = −5.36, p < .001, d = 0.95); (2) both global verbalisable objects and local verbalisable objects were detected more accurately by young participants than by older participants (global: $MD_{young–old}$ = 3.38, 95% CI [2.33, 4.42], z = 8.31, p < .001, d = 2.01; local: $MD_{young–old}$ = 2.14, 95% CI [0.96, 3.31], z = 4.68, p < .001, d = 1.27). See Figure 2.3B left panel.

2.3.4 Nonverbalisable Shapes

For the stimulus category of nonverbalisable shapes, with one exception there were similar results overall for RT and accuracy. For RT, there was a significant main effect of Level, $\chi^2(1) = 17.09$, p < .001, but there were no significant main effects of Age Group (p = .47) or Visual Field (p = .66). For accuracy, there were significant main effects of Level, $\chi^2(1) = 6.09$, p = .01, Visual Field, $\chi^2(1) = 4.36$, p = .04, and Age Group, $\chi^2(1) = 36.52$, p < .001. Results for all interaction effects relevant to the two research questions for the category of nonverbalisable shapes are presented below.

2.3.4.1 Right-Left Hemisphere Asymmetry for Global-Local Processing in Nonverbalisable Shapes. For RT, there was a significant Level × Visual Field interaction, $\chi^2(1) = 3.91$, $p = .048$, and a significant Level × Visual Field × Age Group interaction, $\chi^2(1) = 5.34$, $p = .02$, but there was no Visual Field × Age Group interaction ($p = .08$). These results indicated that although there were RT differences in detecting global and local nonverbalisable shapes in the LVF/RH and RVF/LH, there were also age-group differences in hemispheric asymmetry. Planned additional analyses within each of the two age groups (young, older) were conducted to examine the significant Level × Visual Field × Age Group interaction. In young participants, there was a significant Level × Visual Field interaction, $\chi^2(1) = 5.51$, $p = .02$, whereas in older participants, there was no significant Level × Visual Field interaction ($p = .93$). None of the post hoc pairwise comparisons for the Level × Visual Field interaction in young participants reached significance (all ps ≥ .11). See Figure 2.2C right panel.

For accuracy, there was a significant Level × Visual Field interaction, $\chi^2(1) = 6.17$, $p = .01$, but there was no significant Visual Field × Age Group interaction ($p = .38$) nor was there a Level × Visual Field × Age Group interaction ($p = .06$). These results indicated that although there were accuracy differences in detecting global and local nonverbalisable shapes in the LVF/RH and RVF/LH, there were no age-group differences in hemispheric asymmetry. Post hoc pairwise comparisons for the Level × Visual Field interaction provided accuracy evidence for LH specialisation for local processing in both young and older participants, but no accuracy evidence for RH specialisation for global processing was found: local nonverbalisable shapes were detected more accurately in the RVF/LH than in the LVF/RH (local: $MD_{LVF/RH–RVF/LH} = 0.49$, 95% CI [0.10, 0.87], $z = 3.20$, $p = .008$, $d = 0.26$), but there were no accuracy differences in detecting global nonverbalisable shapes in the LVF/RH than in the RVF/LH ($p = .99$). See Figure 2.3C right panel.

2.3.4.2 Age-Related Local-Processing Bias in Nonverbalisable Shapes. For RT, there was a significant Level × Age Group interaction, $\chi^2(1) = 45.74$, $p < .001$. Post hoc pairwise comparisons indicated that: (1) young participants demonstrated no RT differences in detecting global and local nonverbalisable shapes (young: $MD_{global–local} = −8.11$ ms, 95% CI [−32.44, 16.20], $z = −0.86$, $p = .83$, $d = 0.11$), whereas older participants

were faster in detecting local nonverbalisable shapes than global nonverbalisable shapes (older: $MD_{global–local}$ = 60.55 ms, 95% CI [37.80, 83.29], z = 6.84, p < .001, d = 0.82); (2) there were no RT differences between young and older participants in detecting global nonverbalisable shapes (global: $MD_{young–old}$ = 18.94 ms, 95% CI [−10.2, 48.07], z = 1.67, p = .34, d = 0.26), but local nonverbalisable shapes were detected faster by older participants than by young participants (local: $MD_{young–old}$ = 33.50 ms, 95% CI [7.64, 59.40], z = 3.33, p < .001, d = 0.45). See Figure 2.2C left panel.

For accuracy, there was a significant Level × Age Group interaction, $\chi^2(1)$ = 22.57, p < .001. Post hoc pairwise comparisons indicated that: (1) young participants demonstrated no accuracy differences in detecting global and local nonverbalisable shapes (young: $MD_{global–local}$ = 0.56, 95% CI [−0.44, 1.56], z = 1.45, p = .47, d = 0.30), whereas older participants were more accurate in detecting local nonverbalisable shapes than global nonverbalisable shapes (older: $MD_{global–local}$ = −1.82, 95% CI [−2.65, −0.99], z = −5.64, p < .001, d = 0.98); (2) global nonverbalisable shapes were detected more accurately by young participants than by older participants (global: $MD_{young–old}$ = 2.91, 95% CI [1.99, 3.82], z = 8.18, p < .001, d = 1.06), but there was no accuracy differences between young and older participants in detecting local nonverbalisable shapes (local: $MD_{young–old}$ = 0.53, 95% CI [−0.50, 1.56], z = 1.32, p = .55, d = 0.29). See Figure 2.3C left panel.

2.3.5 Summary of Results

2.3.5.1 Right-Left Hemisphere Asymmetry for Global-Local Processing. Overall, our findings indicated that there was support (RT and/or accuracy) for hemispheric asymmetry for global-local processing (RH-global specialisation and LH-local specialisation) in both young and older participants. For letters, both young and older participants were significantly faster in detecting global letters in the LVF/RH compared to the RVF/LH, and in detecting local letters in the RVF/LH compared to the LVF/RH. There was no support in the accuracy data for hemispheric asymmetry for letters. For verbalisable objects, both young and older participants were significantly more accurate in responding to global verbalisable objects in the LVF/RH compared to the RVF/LH, and in responding to local verbalisable objects in the RVF/LH compared to the LVF/RH. But

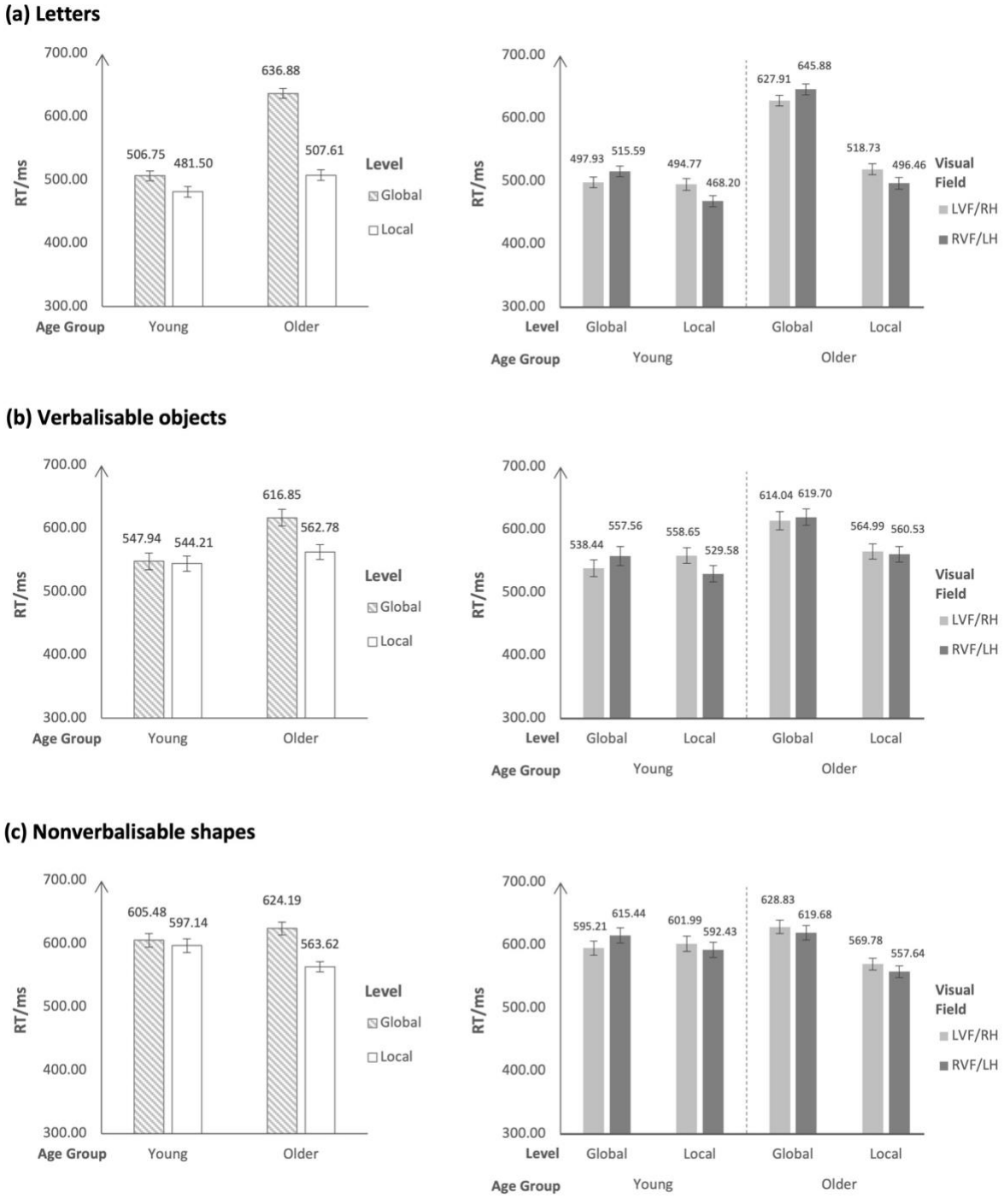
only young participants were significantly faster in detecting global verbalisable objects in the LVF/RH compared to the RVF/LH, and in detecting local verbalisable objects in the RVF/LH compared to the LVF/RH. In contrast to the significant findings for hemispheric asymmetry in letters and verbalisable objects, the findings for nonverbalisable shapes indicated support only for LH-local specialisation: both young and older participants were significantly more accurate in responding to local nonverbalisable shapes in the RVF/LH compared to the LVF/RH. There was no support in the RT or accuracy data for RH-global specialisation for nonverbalisable shapes.

2.3.5.2 Age-Related Local-Processing Bias. Overall, the within-group comparisons indicated that there was support for a local-processing bias in older participants, in that older participants were significantly faster and more accurate in detecting local-level stimuli compared to global-level stimuli across all three stimulus categories. In contrast, young participants—with one exception—demonstrated no RT or accuracy differences in detecting global-level and local-level stimuli. The one exception was for letters, where young participants were faster in detecting the local letters compared to the global letters.

Overall, the between-group comparisons for local-level stimuli indicated that—with three exceptions—there were no RT or accuracy differences found between the two age groups. The three exceptions were as follows: young participants were faster in detecting local letters compared to older participants; young participants were more accurate in detecting local verbalisable objects compared to older participants; older participants were faster in detecting local nonverbalisable shapes compared to young participants. The between-group comparisons for global-level stimuli indicated that—with one exception—young participants were faster and/or more accurate compared to older participants. The one exception was for global nonverbalisable shapes, where there were no RT differences between the two age groups.

Figure 2.2

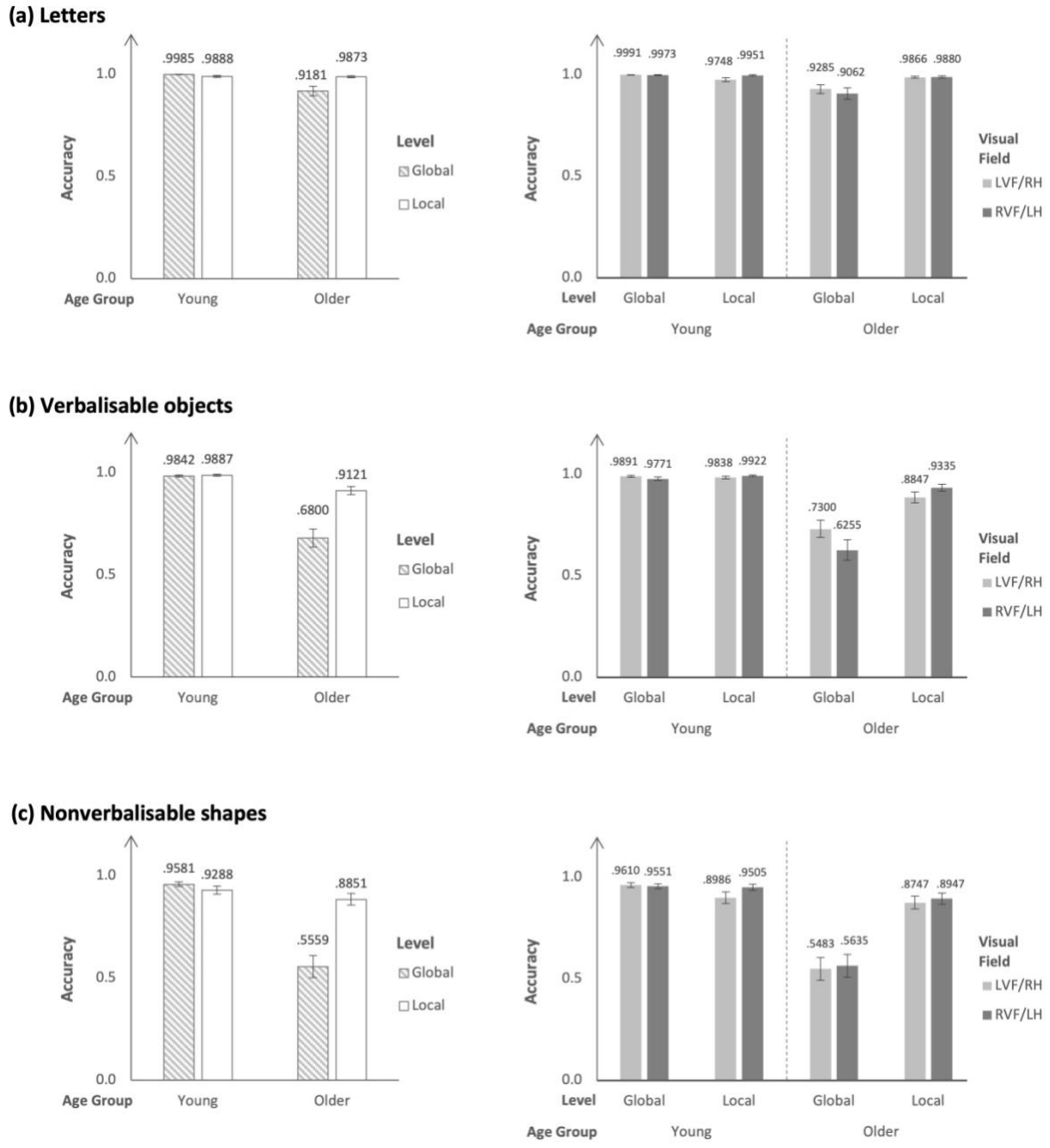
Estimated Marginal Means and Standard Errors for the Reaction Time Data



Note. Left panels present the results for Age Group by Level, and right panels present the results for Age Group by Level by Visual Field.

Figure 2.3

Estimated Marginal Means and Standard Errors for the Accuracy Data



Note. Left panels present the results for Age Group by Level, and right panels present the results for Age Group by Level by Visual Field.

2.4 Discussion

In the present study, we examined hemispheric asymmetry for global-local processing in young and older participants with hierarchical figures from three different stimulus categories (letters, verbalisable objects, and nonverbalisable shapes). For letters and verbalisable objects, we found that regardless of stimulus category, young and older participants demonstrated RH-global specialisation (i.e., global-level stimuli were detected faster and/or more accurately in the LVF/RH compared to the RVF/LH) and LH-local specialisation (i.e., local-level stimuli were detected faster and/or more accurately in the RVF/LH compared to the LVF/RH). For nonverbalisable shapes, young and older participants demonstrated LH-local specialisation, but we found no evidence for RH-global specialisation.

For older participants, in addition to finding RH-global specialisation and LH-local specialisation for letters and verbalisable objects, we found a local-processing bias (i.e., local-level stimuli detected faster and/or more accurately compared to global-level stimuli) for all three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes). First, our results support findings from previous studies (e.g., Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002) that have compared older adults' own performance differences in global-local processing (i.e., within-group comparisons) and found a local-processing bias. Second, our results extend previous findings because we compared the older participants' performance with that of young participants (i.e., between-group comparisons). Older participants were slower and/or less accurate when responding to global-level stimuli, but their responses to local-level stimuli were comparable to that of young participants. Furthermore, to the best of our knowledge, this is the first demonstration that, across three different stimulus categories, older participants' slower and/or less accurate global-processing performance was not specific to stimuli presented in the LVF/RH.

2.4.1 Effects of Stimulus Category on Hemispheric Asymmetry for Global-Local Processing

Our experiment setup allowed us to investigate two competing accounts of hemispheric asymmetry in global-local processing—the stimulus-independent account and the stimulus-dependent account. The s*timulus-independent account* suggests that the stimulus category does not influence hemispheric asymmetry (e.g., Brederoo et al., 2017), whereas the *stimulus-dependent account* suggests that hemispheric asymmetry is influenced by the verbal-visuospatial processing demands associated with the stimulus category (e.g., Fink, Marshall, et al., 1997; Kéïta & Bedoin, 2011).

2.4.1.1 Letters and Verbalisable Objects. In young participants, our findings for letters and verbalisable objects demonstrated the predicted pattern of RH-global specialisation and LH-local specialisation. These findings are in line with previous behavioural studies reporting RH-global specialisation and LH-local specialisation in young adults: for letters (e.g., RT: Hübner, 1998; Yovel et al., 2001); for verbalisable objects (e.g., RT: Oken et al., 1999; RT and accuracy: Peterson & Peterson, 2014); and for both letters and verbalisable objects (accuracy: Brederoo et al., 2017). Our findings for letters are also in line with the neuroimaging data from Fink, Halligan, et al. (1997) and Fink, Marshall, et al. (1997) and the behavioural data from Kéïta and Bedoin (2011). But our findings for verbalisable objects did not replicate these researchers' findings of a reversed pattern of hemispheric asymmetry (i.e., RH-*local* specialisation and LH-*global* specialisation). Brederoo et al. (2017) have argued that the reversal of hemispheric asymmetry for verbalisable objects in the study by Fink, Marshall, et al. (1997) and by Kéïta and Bedoin (2011) may have been a result of two confounding factors—greater visual complexity of the hierarchical verbalisable objects compared to that of the hierarchical letters, and the greater number of local-level stimuli used in the hierarchical objects. In the present study, we did not observe a reversal of hemispheric asymmetry for verbalisable objects, even though we believe our hierarchical verbalisable objects were visually more complex than our hierarchical letters. Therefore, we argue that the reversal of hemispheric asymmetry for verbalisable objects may more likely relate to the number of local-level stimuli used in previous studies.

Brederoo et al.'s (2017) hierarchical letter was composed of seven to 13 local-level stimuli, and the hierarchical verbalisable object was composed of eight to 12 local-level stimuli. In contrast, in the two studies by Fink, Halligan, et al. (1997) and Fink, Marshall, et al. (1997), the hierarchical letter was composed of 11 to 18 local-level stimuli but the hierarchical verbalisable object was composed of 47 to 49 local-level stimuli. Similarly, in the study by Kéïta and Bedoin (2011), the hierarchical letter was composed of 16 to 26 local-level stimuli but the hierarchical verbalisable object was composed of 24 to 32 local-level stimuli (also see Table 2.1). In the present study, our hierarchical letter was composed of seven to 10 local-level stimuli, and our hierarchical verbalisable object was composed of 10 to 15 local-level stimuli. Perhaps more notable is that the number of local-level stimuli (10 to 15) in our hierarchical verbalisable object was similar to the number of local-level stimuli (8 to 12) in the study by Brederoo et al., who also did not find a reversal of hemispheric asymmetry. As explained by Brederoo et al., hierarchical figures with a large number of local-level stimuli may lead to the reversal of hemispheric asymmetry because large numbers of local-level stimuli may result in local-level stimuli being perceived as the textural background that makes up the global-level stimulus, rather than as distinct individual components. These effects would reduce the reliability of finding hemispheric asymmetry for global-local processing (Kimchi & Merhav, 1991).

In older participants, as in young participants, our findings for letters and verbalisable objects demonstrated the predicted pattern of RH-global specialisation and LH-local specialisation. Our findings with verbalisable objects are in line with Oken et al. (1999), who used verbalisable objects as stimuli and conducted the only other previous behavioural study with a divided visual field presentation to examine hemispheric asymmetry for global-local processing in older adults. Our findings with letters extend the findings from Oken et al. with their verbalisable objects, and confirm that older adults demonstrate RH-global specialisation and LH-local specialisation for both letters and verbalisable objects.

2.4.1.2 Nonverbalisable Shapes. In both young and older participants, our accuracy data for nonverbalisable shapes demonstrated LH-local specialisation but there was no evidence (neither for RT nor accuracy) found for RH-global specialisation

(i.e., there were no performance differences in detecting global-level nonverbalisable shapes presented in the LVF/RH compared to those presented in the RVF/LH). Martinez et al. (1997) conducted the only previous behavioural study examining hemispheric asymmetry for global-local processing of nonverbalisable shapes, and like us, they used a divided visual field presentation. In young adults, they found LH-local specialisation in the absence of RH-global specialisation for nonverbalisable shapes. One possible explanation for these findings with nonverbalisable shapes may be the difficulty of the stimulus category. Nonverbalisable shapes are unfamiliar novel shape patterns, which are processed less automatically than letters or verbalisable objects. Importantly, although Martinez et al. found RT evidence for LH-local specialisation of nonverbalisable shapes, their neuroimaging findings demonstrated evidence not only of greater LH activation for local processing (LH-local specialisation) but also of greater RH activation for global processing (RH-global specialisation). This inconsistency between their RT and neuroimaging findings for hemispheric asymmetry also suggests that behavioural measures may not be sensitive enough to detect RH-global specialisation for nonverbalisable shapes.

In young participants, our findings indicated longer RT for nonverbalisable shapes compared to letters and verbalisable objects, and the RT for nonverbalisable shapes were longer than those reported by Martinez et al. (1997).[8] In the present study, the longer RT for nonverbalisable shapes may reflect overall greater processing time, thus making it difficult to isolate the specific effects of each hemisphere for processing global-local information. Importantly, the longer RT for nonverbalisable shapes were also consistently found in our pilot study (see Footnote 5), where young participants were slower at detecting nonverbalisable shapes compared to verbalisable objects, regardless of whether they performed the hierarchical nonverbalisable shapes experiment first and the hierarchical verbalisable objects experiment second or in the reverse order. One factor that may have contributed to the longer RT in the present study

[8] Martinez et al. (1997) reported RT data for the Level × Visual Field interaction in young participants: global nonverbalisable shapes in the LVF/RH = 544 ms; global nonverbalisable shapes in the RVF/LH = not reported; local nonverbalisable shapes in the LVF/RH = 586 ms; local nonverbalisable shapes in the RVF/LH = 551 ms (see p. 1688).

could be the greater task difficulty involved in the divided-attention paradigm compared to the focused-attention paradigm used by Martinez et al. It has been suggested (see Müller-Oehring et al., 2007) that a divided-attention paradigm poses greater task difficulty because it requires concurrent allocation of attention to both the global level and the local level of the stimulus, in contrast to the allocation of attention to only one processing level in a focused-attention paradigm. We adopted a divided-attention paradigm because Yovel et al. (2001) reported that a divided-attention (as compared to a focused-attention) paradigm produces a greater effect size for hemispheric asymmetry for global-local processing. However, the findings from Yovel et al. were based on young adults' performance with letters, and they did not test the effects of other stimulus categories, or the effects of ageing. Another factor that may have contributed to our longer RT for nonverbalisable shapes, compared to those of Martinez et al., is that we had two nonverbalisable-shape targets, whereas they had only one. We suggest that the greater number of targets in the present study increased the difficulty of our task compared to that of Martinez et al.'s study, and this difference in task difficulty was reflected in the participants' RT performance.

Considering the limited amount of research on hemispheric asymmetry for global-local processing of nonverbalisable shapes, future research is needed to examine systematically the effects of task difficulty (e.g., a divided- *versus* focused-attention paradigm; number of targets requiring a response in the experiment) on finding RH-global specialisation and LH-local specialisation in different age groups.

2.4.2 Age-Related Local-Processing Bias

Our experiment setup also allowed us to investigate the extent to which the right-hemisphere ageing hypothesis (i.e., the RH is more vulnerable to ageing than the LH) can explain previous findings of a local-processing bias in older adults (i.e., local-level stimuli detected faster and/or more accurately compared to global-level stimuli).

Given the proposal that the RH is more vulnerable to ageing than the LH (Albert, 1981; Brown & Jaffe, 1975; Klisz, 1978), we sought to determine whether the local-processing bias we found in older participants could be attributed to age-related changes

in RH functioning. Our within-group analyses revealed that older participants were faster and more accurate in detecting local-level stimuli compared to global-level stimuli for all three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes). These findings are in line with previous behavioural studies reporting a local-processing bias in older adults: for letters (e.g., RT and accuracy: Lux et al., 2008); for numbers (e.g., RT: Slavin et al., 2002); and for verbalisable objects (e.g., RT: Oken et al., 1999; accuracy: Insch et al., 2012). Our between-group analyses revealed that older participants were slower and less accurate in detecting global-level stimuli compared to young participants, but there were no age-group differences in detecting local-level stimuli. The local-processing bias in older adults reported in previous studies was based on performance differences between global and local processing in the data of the older adults (i.e., within-subject comparisons, as there was no report of age-group differences). Our findings confirm that older participants demonstrate a local-processing bias regardless of stimulus category and that this local-processing bias is driven not by better performance in local processing but by worse performance in global processing.

Oken et al. (1999) tested young and older participants with verbalisable objects using a divided visual field presentation. In addition to finding a local-processing bias in older adults, Oken et al. also reported that older participants did not demonstrate age-related changes in overall performance in the LVF/RH as compared to the RVF/LH. They suggested that their findings did not support the right-hemisphere ageing hypothesis. They further argued that if the local-processing bias in older adults was associated with the RH ageing process, then the older adults' RT performance for stimuli presented in the LVF/RH should be worse, regardless of the global-local processing level. We found support for Oken et al.'s proposal since our older participants demonstrated a local-processing bias for all three stimulus categories. Importantly, their overall RT and accuracy performance for stimuli presented in the LVF/RH was comparable to their performance in the RVF/LH, regardless of whether the stimuli were global stimuli or local stimuli. These findings suggest that there are age-related differences in global processing, but that these age-related differences are evident for stimuli presented in the LVF/RH and in the RVF/LH.

Two alternative explanations have been put forward to explain the local-processing bias observed in older adults—narrowed attention and difficulties with visual processing at greater eccentricities. The first explanation suggests that the local-processing bias in older adults may be a compensatory mechanism for addressing poorer visual input from age-related deterioration in optical structures (Kosslyn et al., 1999; see Oken et al., 1999). If attention is narrowed with age, older adults will demonstrate better performance for local processing compared to young adults. However, our findings did not support this, as we observed that the local-processing bias in older participants was driven not by faster and more accurate performance for local processing but instead by slower and less accurate performance for global processing. The second explanation suggests that the local-processing bias in older adults may relate to difficulties with visual processing at greater eccentricities (Cerella, 1985; Hartley & McKenzie, 1991). Oken et al. (1999) suggested that in a divided visual field presentation, the average position of the global-level stimulus is farther from central fixation (i.e., at a greater eccentricity) compared to the local-level stimuli that are closer to central fixation. One limitation to be considered with this proposal is that previous studies reporting a local-processing bias in older adults have also presented their stimuli centrally (e.g., Lux et al., 2008; Slavin et al., 2002), in which the position of the global stimulus was at central fixation.

Our behavioural findings of age-related differences for global processing in older participants are consistent with the electrophysiological study conducted by Lithfous et al. (2016). They reported behavioural and ERP (event-related potentials) data for the processing of centrally-presented hierarchical letters in young and older participants. Their RT data confirmed an age-related local-processing bias, in which older adults were faster at detecting local-level letters compared to global-level letters. Their ERP data indicated that, while young and older adults demonstrated the same amplitudes for the early N2 component (~250 ms–340 ms), older adults demonstrated reduced amplitudes for the later P300 component (~340 ms–480 ms). The P300 component has been suggested to relate to perceptual grouping of local-level stimuli for the identification of the global-level stimulus in hierarchical figures, and this occurs at a late stage of global-local processing (Dalrymple et al., 2009). The findings from Lithfous et al. suggest that the local-processing bias in older adults may be driven by age-related changes in global

processing that are associated with the P300 component. To the best of our knowledge, no ERP study to date has investigated global-local processing in older adults in the context of hemispheric asymmetry. Future research could consider incorporating ERP data with behavioural measures of hemispheric asymmetry (i.e., a divided visual field presentation) to investigate whether age-related changes in RH functioning can be observed specifically for the P300 component.

2.5 Conclusion

The present study is the first to examine hemispheric asymmetry for global-local processing in young and older participants with hierarchical figures from three different stimulus categories (letters, verbalisable objects, and nonverbalisable shapes) in a within-subjects design using a divided-attention paradigm and divided visual field unilateral presentation. For letters and verbalisable objects, our findings in both age groups support the *stimulus-independent* account (e.g., Brederoo et al., 2017) and do not support the stimulus-dependent account (e.g., Fink, Halligan, et al., 1997; Fink, Marshall, et al., 1997). For letters and verbalisable objects, our findings in young and older participants indicate that hemispheric asymmetry for global-local processing demonstrates the same pattern of RH-global specialisation and LH-local specialisation regardless of stimulus category. However, for nonverbalisable objects, our findings in young and older participants reveal LH-local specialisation in the absence of RH-global specialisation. Further investigation is warranted to determine whether this finding can be attributed to the greater task difficulty of the nonverbalisable shapes. Our findings in older participants confirmed there was a local-processing bias across all three stimulus categories (letters, verbalisable objects, and nonverbalisable shapes), and that this local-processing bias was driven not by better performance in local processing but by worse performance in global processing. Importantly, the findings indicate that the age-related differences found were not specific to the LVF/RH when we compared the older adults' own performance in the LVF/RH with that in the RVF/LH. Overall, our findings challenge the right-hemisphere ageing hypothesis, prompting the need for future research to investigate the mechanisms underlying these findings for global processing in older adults.

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Chapter 3 Age-Related Changes in Attentional Orienting for Global-Local Processing

Publication Note

The manuscript for this study is in preparation.

Abstract

The two hemispheres of the brain demonstrate functional asymmetry for attentional processing. Previous research implicates the right hemisphere in difficulties with the directional components of attentional orienting for older adults—greater difficulties with disengaging attention from information on the right side of space to re-orient attention to information on the left, where left-side information is proposed to be processed by the right hemisphere. We investigated whether these age-related right-hemisphere difficulties extend to the non-directional components of attentional orienting—greater difficulties disengaging attention from information at the local level of an object to re-orient attention to the global level, where global-level information is proposed to be processed by the right hemisphere. Seventy-seven participants (39 young, 38 older) were included in the analysis. Navon hierarchical figures were used in a global-local paradigm, with participants instructed to focus attention either at the global or local level of the hierarchical figure, and to respond 'Yes' if a target appeared at the task-relevant level, or 'No' if no target appeared at the task-relevant level. 'No' responses required disengaging attention from a target at the task-irrelevant level for the purpose of re-orienting attention to the task-relevant level. Compared to young participants, older participants demonstrated worse 'No' response performance when targets appeared at the task-irrelevant local level than at the task-irrelevant global level, indicating greater age-related difficulties with disengaging attention from information at the local level of an object than from the global level. These findings extend our current understanding of

right-hemisphere ageing, indicating that healthy ageing influences not only the directional components of attentional orienting but also the non-directional components.

3.1 Introduction

Our visual environment consists of hierarchical structures—a scene with many trees can be perceived as either an entire forest or as individual trees within the forest. To navigate in such a complex visual environment, our visual system relies on attentional mechanisms to orient attention between the different levels of the hierarchical structures. One such attentional mechanism is global-local processing, which involves directing attention either globally (i.e., to the overall visual scene, such as the forest) or locally (i.e., to the finer elements within the scene, such as the individual trees or even the leaves on the tree). Navon's (1977) hierarchical figures have been widely used to examine global-local processing. These hierarchical figures consist of a large stimulus (e.g., a large 'global-level' letter 'H') made up of several smaller stimuli, which can be either congruent with the large stimulus (e.g., local-level 'H' letters) or incongruent with the large stimulus (e.g., local-level 'T' letters).

Hierarchical figures were initially used to investigate the global-local processing bias, a bias which refers to the relative efficiency of processing global information as compared with local information. In Navon's (1977) study, a hierarchical figure was presented centrally in each trial. Participants were instructed to attend either to the global level or to the local level of the hierarchical figure, and to make a two-alternative forced-choice identification response to indicate whether a target (either 'H' or 'T') appeared at the task-relevant level. Navon reported two key findings. First, participants were faster overall at identifying global letters compared to local letters, which was interpreted to indicate a global-processing bias. Second, when participants were required to identify letters at the local level, they were slower if the letters at the global level and local level of the hierarchical figure were incongruent (e.g., a global 'H' letter made up of local 'T' letters), as compared to when the letters at the two levels were congruent (e.g., a global 'H' letter made up of local 'H' letters). These findings were

interpreted to mean that there was a global-to-local interference effect, indicating that the conflicting global information inhibited local-letter identification. In contrast, when participants were required to identify letters at the global level, these reaction time differences did not exist. These findings were interpreted to mean that there was no local-to-global interference effect, as the conflicting local information did not inhibit global-letter identification. Taken together, the overall findings from Navon's study—for a global-processing bias and a global-to-local interference effect—provided support for the notion of a global-precedence effect, that "perception proceeds from global analysis to more and more fine-grained analysis" (p.381). Later studies have challenged Navon's interpretation of the global-precedence effect, demonstrating that the observation of a global-processing bias and a global-to-local interference effect can be manipulated by altering the density of the local-level stimuli in the hierarchical figures (Dalrymple et al., 2009; Kinchla & Wolfe, 1979; Martin, 1979b; Schlösser et al., 2009; Yovel et al., 2001).

Hierarchical figures have also been used to investigate hemispheric asymmetry for global-local processing. A divided visual field design, used in a typical global-local processing paradigm, consists of a hierarchical figure presented unilaterally either to the left visual field (LVF) or to the right visual field (RVF). The logic behind the divided visual field design was that hierarchical figures briefly presented to the LVF will be processed first by the right hemisphere (RH), and hierarchical figures briefly presented to the RVF will be processed first by the left hemisphere (LH) (Beaumont, 1982; Bourne, 2006). Behavioural findings (e.g., Brederoo et al., 2017; Brederoo et al., 2019; Chen et al., 2024; Hübner, 1998; Martin, 1979a; Sergent, 1982; Yovel et al., 2001) revealed that young adults demonstrated: (1) better performance in detecting global stimuli presented to the LVF compared to the RVF, indicating right hemisphere specialisation for global processing (RH-global specialisation); and (2) better performance in detecting local stimuli presented to the RVF compared to the LVF, indicating left hemisphere specialisation for local processing (LH-local specialisation). To the best of our knowledge, only three studies (Chen & Aimola Davies, 2025; Chen et al., 2024; Oken et al., 1999) have examined hemispheric asymmetry for global-local processing in young and older adults. All three studies reported that young and older adults demonstrated better performance in detecting global stimuli presented to the LVF compared to the RVF (i.e., RH-global

specialisation) and better performance in detecting local stimuli presented to the RVF compared to the LVF (i.e., LH-local specialisation). These findings indicated that that hemispheric asymmetry for global-local processing remains intact with age.

3.1.1 Age-Related Differences in Attentional Orienting for Global-Local Processing

Although hemispheric asymmetry for global-local processing remains intact with age, healthy ageing has been shown to influence the relative efficiency of processing global-level information as compared with local-level information. These findings have been interpreted to mean that there is an age-related local-processing bias in older adults (Chen & Aimola Davies, 2025; Chen et al., 2024; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002), which is characterised by two key findings. First, for within age-group comparisons, older adults demonstrated overall better performance in detecting local stimuli compared to global stimuli, whereas young adults demonstrated either no performance differences in detecting local stimuli and global stimuli (Chen & Aimola Davies, 2025; Chen et al., 2024; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999) or better performance in detecting global stimuli compared to local stimuli (Slavin et al., 2002). Second, for between age-group comparisons, older adults demonstrated worse performance in detecting global stimuli compared to young adults, whereas there were no age-group performance differences in detecting local stimuli (Chen & Aimola Davies, 2025; Chen et al., 2024). The overall findings indicated there were greater age-related differences in global processing, whereas local processing remained relatively intact across the adult lifespan. One explanation that has been put forward for these age-related differences in global processing is the right-hemisphere ageing hypothesis, which proposes that RH functions (e.g., global processing) are more vulnerable to ageing than LH functions (e.g., local processing) (Albert, 1981; Brown & Jaffe, 1975; Klisz, 1978).

To the best of our knowledge, no study has directly examined the effects of healthy ageing on attentional orienting within a global-local processing paradigm. Attentional orienting is typically examined using a spatial-cueing paradigm (Posner, 1980; Posner et al., 1980), which investigates the directional component of attentional orienting to the LVF and to the RVF. In a standard spatial-cueing paradigm, two boxes are presented, one

positioned to the left side (i.e., in the LVF) and the other one to the right side (i.e., in the RVF) of a central fixation cross. On each trial of a target-present condition, a target appears in one of the two boxes preceded by a cue that either correctly indicates the target location (valid-cue condition) or incorrectly indicates the opposite location (invalid-cue condition). The difference in reaction time between the valid-cue condition and the invalid-cue condition reflects participants' efficiency at disengaging attention from the invalid-cued location and re-orienting attention to the unexpected target location. Difficulties with disengaging attention from an invalid cue in the RVF for the purpose of re-orienting attention to a target in the LVF (as compared to disengaging attention from an invalid cue in the LVF for the purpose of re-orienting attention to a target in the RVF) have been reported both in patients with unilateral RH damage (Morrow & Ratcliff, 1988; Posner et al., 1984; Posner et al., 1987; also see Aimola Davies, 2004; Bartolomeo & Sylvie, 2002; Loiser & Klein, 2001 for reviews) and in healthy older adults (Guilbert et al., 2019).

These attentional orienting findings with the spatial-cueing paradigm (Guilbert et al., 2019; Morrow & Ratcliff, 1988; Posner et al., 1984; Posner et al., 1987) have two important implications. First, the finding that patients with unilateral RH damage demonstrated difficulties with disengaging attention from an invalid cue in the RVF indicates that the ability to disengage attention from the RVF for the purpose of re-orienting attention to the LVF depends on intact RH functioning. Second, the finding that healthy older adults demonstrated difficulties that were similar to patients with unilateral RH damage, who have difficulties disengaging attention from an invalid cue in the RVF for the purpose of re-orienting attention to the LVF, provides support for the proposal that RH functions are more vulnerable to healthy ageing than LH functions. Consequently, we asked: *Do the known age-related difficulties in healthy older adults tested with the spatial-cueing paradigm extend to age-related difficulties with other visual attentional paradigms, such as the global-local processing paradigm?* Unlike the spatial-cueing paradigm, which measures the directional component of visual attention—attentional re-orienting from the RVF to the LVF (a RH function) as compared to attentional re-orienting from the LVF to the RVF (a LH function), the global-local processing paradigm measures the non-directional component of visual attention—attentional processing at

the global level (a RH function) as compared to attentional processing at the local level (a LH function) (see Aimola Davies, 2004; Halligan & Marshall, 1994a, 1994b).

One approach for examining these age-related differences for global-local processing is to adopt a paradigm that requires participants to focus attention either at the global level of a hierarchical figure (i.e., a global-focused attention task) *or* at the local level of a hierarchical figure (i.e., a local-focused attention task), and to detect whether or not a target stimulus appears at the task-relevant level. In this experiment design, the global level and the local level of the hierarchical figure are made up of a target stimulus at one level and a distractor stimulus at the other level. A Yes/No detection-response mode was used, with a 'Yes' response indicating that the target stimulus did appear at the task-relevant level, and a 'No' response indicating that the target stimulus did not appear at the task-relevant level. The 'No' response to the target presented at the task-irrelevant level in this focused-attention version of the global-local processing paradigm is comparable to the invalid-cue condition of the spatial-cueing paradigm. In the spatial-cueing paradigm, when a participant's attention is first drawn to an invalid-cue location in the RVF, to make a correct response, they must disengage their attention from this invalid-cue location in the RVF for the purpose of re-orienting attention to the correct target location in the LVF. In the global-focused condition of the global-local processing paradigm, when a participant's attention is first drawn to a task-irrelevant *local-level* target in the hierarchical figure, to make a correct 'No' response (indicating that the target stimulus did not appear at the task-relevant global level), they must disengage their attention from this task-irrelevant *local-level* target for the purpose of re-orienting their attention to the task-relevant global level of the hierarchical figure.

Müller-Oehring et al. (2007) and Lux et al. (2008) have adopted a focused-attention version of the global-local processing paradigm, with a Yes/No detection-response mode, to examine age-related differences in global-local processing [1], but neither study

[1] Most studies examining age-related differences in global-local processing (Agnew et al., 2016; Bruyer & Scailquin, 2000; Bruyer et al., 2003; Georgiou-Karistianis et al., 2006; Insch et al., 2012; Roux & Ceccaldi, 2001; Slavin et al., 2002) have used Navon's (1977) experiment design, the focused-attention version of the global-local processing paradigm with a two-alternative forced-choice identification response mode. In this design, participants are instructed to focus on one level of the hierarchical figure (i.e., either the global

directly addressed the effects of attentional orienting or re-orienting within a global-local processing paradigm. Müller-Oehring et al. tested 37 participants, aged 26 to 79 years, and conducted a correlational analysis. They reported that, with increasing age, there was a trend toward poorer task performance for correctly making a 'No' response in the global-focused condition when a target was presented at the task-irrelevant local level of the hierarchical figure. Although their correlational findings were not significant (p = .06, p.196), it is possible that there were age-related difficulties with disengaging attention from local-level information for the purpose of re-orienting attention to global-level information. Importantly, Müller-Oehring et al. did not report results for the comparison condition (i.e., task performance for correctly making a 'No' response in the local-focused condition when a target was presented at the task-irrelevant global level of the hierarchical figure), which required disengaging attention from the task-irrelevant global-level information for the purpose of re-orienting attention to the task-relevant local-level information of the hierarchical figure. Similarly, Lux et al. tested 21 young participants and 21 older participants, but they did not directly compare young and older participants' performance in the condition requiring disengaging attention from the task-irrelevant global-level information (i.e., a 'No' response in the global-focused condition when a target was presented at the task-irrelevant local level) and the condition requiring disengaging attention from the task-irrelevant local-level information (i.e., a 'No' response in the local-focused condition when a target was presented at the task-irrelevant global level).

level *or* the local level) and identify which of two targets (e.g., identify whether it is the target letter 'H' or the target letter 'T') appears at the task-relevant level. Critically, one of the two targets is always presented at the task-relevant level. This stimulus design is necessary because each of the two forced-choice identification responses corresponds to each of the two targets (e.g., 'H' response and 'T' response). Therefore, a target must be presented at the task-relevant level for a valid response to be made. If a distractor (e.g., a distractor letter 'D') is presented at the task-relevant level, a valid response cannot be made. As a result, this experiment design does not involve the necessary conditions that test whether participants have disengaged attention from a target at the task-irrelevant level for the purpose of re-orienting attention to the task-relevant level.

3.1.2 The Present Study

In the present study, we used Navon's (1977) hierarchical figures in a focused-attention version of the global-local processing paradigm, and a Yes/No detection-response mode. Participants focused on one processing level of the hierarchical figure (i.e., participants focused either on the global level *or* the local level) and were instructed to make a 'Yes' response when a target appeared at the task-relevant level, and to make a 'No' response when a target did not appear at the task-relevant level.

The main research question addressed the literature gap regarding age-related differences in attentional orienting for global-local processing. The current study builds on findings from previous research using a spatial-cueing paradigm, in which healthy older adults demonstrated greater difficulties with the RH function of disengaging attention from the RVF for the purpose of re-orienting attention to the LVF, as compared with the LH function of disengaging attention from the RVF for the purpose of re-orienting attention to the LVF (Guilbert et al., 2019; also see similar findings from patients with unilateral RH damage: Morrow & Ratcliff, 1988; Posner et al., 1984; Posner et al., 1987). We investigated whether healthy older adults demonstrated greater difficulties with the RH function of disengaging attention from the local level of a hierarchical figure for the purpose of re-orienting attention to the global level, as compared with the LH function of disengaging attention from the global level of a hierarchical figure for the purpose of re-orienting attention to the local level (see Halligan & Marshall, 1994a, 1994b). We asked: *When comparing young with healthy older adults, do healthy older adults demonstrate greater difficulties when a target appeared at the task-irrelevant local level and they were required to disengage their attention from the target at the task-irrelevant local level for the purpose of re-orienting their attention to the task-relevant global level to make a correct 'No' response indicating that no target appeared at the task-relevant level* (as compared to when a target appeared at the task-irrelevant global level and they were required to disengage their attention from the target at the task-irrelevant global level for the purpose of re-orienting their attention to the task-relevant local level to make a correct 'No' response indicating that no target appeared at the task-relevant level)?

We also investigated hemispheric asymmetry for global-local processing. Previous studies (Chen & Aimola Davies, 2025; Chen et al., 2024; Oken et al., 1999) have used a Go/No-go response mode (i.e., respond when a target appears, do not respond when no target appears), and found RH-global specialisation and LH-local specialisation in both young and older adults. We aimed to provide further support for these hemispheric asymmetry findings using a Yes/No detection-response mode. More specifically, we investigated whether young and older adults would demonstrate RH-global specialisation and LH-local specialisation both for 'Yes' responses, which indicated that a target appeared at the task-relevant level, and for 'No' responses, which indicated that no target appeared at the task-relevant level.

3.2 Methods

3.2.1 Transparency and Openness

We describe the data collection procedure, participant exclusions, sample size determination, experimental manipulation, and the statistical analysis plan in the Methods section. The experiment program was coded in E-Prime (version 2.0.10.353), which is available on request from the corresponding author. The data from this study cannot be publicly available, as informed consent for our study specifies that de-identified participant data will only be accessible to the researchers on this project. This study was not preregistered. The data reported here represent original use and have not been published elsewhere.

3.2.2 Participants

A total of 79 participants were recruited for this study between 2016 to 2018: 39 young participants were recruited from the Australian National University, and 40 older participants were recruited from the University of the Third Age and the broader community in Canberra. All participants self-reported being of European descent and

living in Australia[2]. Participants were excluded from the statistical analyses if they did not meet the following six inclusion criteria:

1. Right-handed, based on the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were considered to be right-handed if their laterality scores were higher than + 40.00.
2. Normal or corrected-to-normal vision, as indicated by in-laboratory testing with a Snellen chart (Snellen, 1868).
3. No history of self-reported neurological impairments.
4. No evidence of cognitive impairment, as assessed by the Montreal Cognitive Assessment (Nasreddine et al., 2005), with a score of 24 or greater indicating intact cognitive functioning in older adults (Pugh et al., 2018; Thomann et al., 2020).
5. Overall accuracy of 75% or greater on *congruent-target* trials (i.e., hierarchical figures with the same target at both the global level and the local level) for which a 'Yes' response was required in both the global-focused condition and the local-focused condition. A 'No' response to a congruent-target trial indicated that the participants either did not discriminate targets from distractors, or they failed to comply with the task instruction to make a 'Yes' response to indicate that a target had appeared at the task-relevant level.
6. Overall accuracy of 75% or greater on *target-absent* trials (i.e., hierarchical figures with no target either at the global level or the local level) for which a 'No' response was required in both the global-focused condition and the local-focused condition. A 'Yes' response to a target-absent trial indicated that the participants either did not discriminate targets from distractors, or they failed to comply with the task instruction to make a 'No' response to indicate that a target did not appear at the task-relevant level.

[2] We chose participants of European descent to ensure cultural consistency across the two age groups, as cultural background has sometimes been shown to make a difference in global-local processing studies with young adults as participants (e.g., McKone et al., 2010).

There were no exclusions for criteria 1, 2, 3, and 4. One older participant was excluded for criterion 5, and one older participant was excluded for criterion 6. The final statistical analyses included a sample of 39 young participants and 38 older participants. See Table 3.1 for the full demographic details. Power analyses using G*Power (version 3.1) (Faul et al., 2007) indicated that a minimum of 35 participants in each of the two age groups was required to achieve 95% power with $\alpha = .05$ [3]. All participants provided written consent prior to participation in the study and received monetary compensation (or course credit for eligible young participants). This study was approved by the Australian National University Human Research Ethics Committee (Protocol 2013/605).

[3] The main research question involved comparing 'No' responses in the global-focused condition when a target was presented at the task-irrelevant local level with 'No' responses in the local-focused condition when a target was presented at the task-irrelevant global level. This comparison was examined in the Focus Level (global-focused, local-focused) × Target Type (target at task-irrelevant level, no target at either level) interaction for the 'No' response condition. Of the two studies (Müller-Oehring et al., 2007; Lux et al., 2008) that adopted the same design as the present study to examine age-related differences in global-local processing, only Müller-Oehring et al. reported on this specific interaction (see p.196). Based on their *F* statistics, we calculated an effect size of $\eta_p^2 = .14$ drawn from a sample of 37 participants aged from 26 to 79 years. We opted for a smaller medium effect size of $\eta_p^2 = .06$ (Cohen, 1988), which requires a larger minimum sample size to achieve the same level of power compared to the larger effect size of $\eta_p^2 = .14$ derived from Müller-Oehring et al. (2007).

Table 3.1

Demographic Information and Task Accuracy for Young and Older Participants Included in the Statistical Analyses

Demographic information	Young participants	Older participants
N	39	38
Female (*n*, %)	26, 66.67%	30, 78.95%
Male (*n*, %)	13, 33.33%	8, 21.05%
Age		
M	19.72	70.08
SD	1.76	5.81
Range	18–23	60–85
Edinburgh Handedness Inventory Scores (*M*, SD)	+ 81.85, 18.65	+81.79, 14.71
Language history [a]		
Monolinguals (*n*, %)	21, 53.85%	23, 60.53%
Bilinguals or multilinguals (*n*, %)	18, 46.15%	15, 39.47%
*Age of second language acquisition (*M, SD*)*	4.78, 3.78	10.17, 6.27
Task accuracy (%)		
Global-focused condition		
Congruent-target trials (Yes)	96.79%	95.15%
Global-target trials (Yes)	85.88%	77.06%
Local-target trials (No)	93.22%	89.56%
Target-absent trials (No)	96.96%	95.72%
Local-focused condition		
Congruent-target trials (Yes)	97.08%	96.38%
Local-target trials (Yes)	95.90%	86.51%
Global-target trials (No)	89.08%	84.21%
Target-absent trials (No)	91.12%	93.67%

Note. 'Yes' responses were required to indicate correctly that a target appeared at the task-relevant level; 'No' responses were required to indicate correctly that no target appeared at the task-relevant level.

[a] Bilingual advantages have been reported for executive function, including tasks involving disengaging attention (see Bialystok & Craik, 2022 for a review). To account for language history, participants who spoke one or more languages fluently in addition to English were considered bilinguals or multilinguals. Second language speaking proficiency was measured by a self-rated seven-point Likert scale (1 = very poor, 2 = poor, 3 = fair, 4 = functional, 5 = good, 6 = very good, 7 = fluent), with a score of 5 or greater considered fluency in a second language. A chi-square test indicated that the proportion of monolingual participants and the proportion of bilingual/multilingual participants did not differ between the young age group and the older age group, $\chi^2(1, N = 77) = 0.35$, $p = .55$, $\phi = -.07$. Age of second language acquisition refers to the age at which the second language was learned for speaking.

3.2.3 Apparatus and Stimuli

Experiments were programmed in E-Prime (version 2.0.10.353) and were presented on a 19-inch monitor (Sony CPD-G420 Multiscan) with an 85 Hz refresh rate and 1280 × 1024 pixels resolution. Participants' reaction time (RT) and accuracy were recorded with a response box (Psychology Software Tools 200A SRB200-08251). A forehead-and-chin rest was used to maintain a 50 cm constant eye-to-screen viewing distance for each participant.

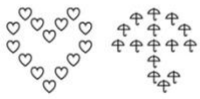
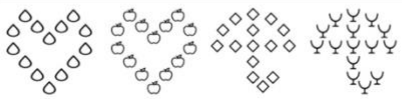
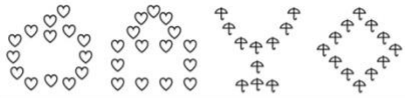
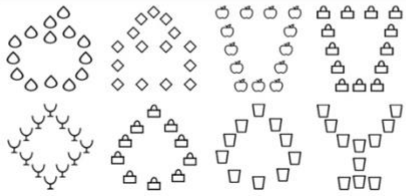
The hierarchical figures consisted of global-level objects (size = 3.33° × 3.87°) that were made up of 10 to 15 local-level objects (size = 0.54° × 0.59°). The size of the global-level and local-level objects in the hierarchical figures was based on Yovel et al.'s (2001) equal salience design (i.e., the global level and local level of the hierarchical figures were equally discriminable, as indicated by RT performance). For the objects making up the hierarchical figures, there were two targets and six distractors. The targets were ♡ (heart) and ☂ (umbrella). The distractors were (apple), (briefcase), (cup), ◇ (diamond), (drop), and (glass). Within each hierarchical figure, targets were either present (i.e., target-present hierarchical figures) or absent (i.e., target-absent hierarchical figures). There were three types of target-present hierarchical figures: congruent-target figures (i.e., the same target presented at both the global level and the local level), global-target figures (i.e., one target presented at the global level and one distractor presented at the local level), and local-target figures (i.e., one target presented at the local level and one distractor presented at the global level). There was only one type of target-absent hierarchical figure, which was made up of two different distractors (i.e., one distractor presented at the global level and a different distractor presented at the local level). In total, there were 18 hierarchical figures: two congruent-target figures, four global-target figures, four local-target figures, and eight target-absent figures. See Figure 3.1 for full details.

The hierarchical figures were presented in black against a white background. For each trial, one hierarchical figure was presented unilaterally either to the LVF or to the

RVF[4]. The medial edge (i.e., the edge closest to central fixation) of the hierarchical figure was positioned either 0.54° to the left or 0.54° to the right of a central fixation cross (size = 0.22° × 0.22°). To prevent afterimages, two post-stimulus masks were presented bilaterally immediately after the presentation of a hierarchical figure. The medial edges of each of the post-stimulus masks were positioned 0.54° to the left and 0.54° to the right of the central fixation cross. Each post-stimulus mask (size = 4.19° × 3.44°) comprised of an array of 6 × 8 small objects (size = 0.43° × 0.43°). The objects used in the post-stimulus masks (e.g., scissors, envelope, bike, file, mailbox, radio, computer mouse) were different from the objects used in the hierarchical figures.

Figure 3.1

Hierarchical Figures and Experiment Design for the Focused-Attention Version of the Global-Local Processing Paradigm, with a Yes/No Detection-Response Mode

Type of hierarchical figure	Stimulus	Accurate response	
		Global-focused condition	Local-focused condition
Congruent-target figures		**Yes** Target appeared at the global level	**Yes** Target appeared at the local level
Global-target figures		**Yes** Target appeared at the global level	**No** Target did not appear at the local level
Local-target figures		**No** Target did not appear at the global level	**Yes** Target appeared at the local level
Target-absent figures		**No** Target did not appear at the global level	**No** Target did not appear at the local level

Note. 'Yes' responses were required to indicate correctly that a target appeared at the task-relevant level; 'No' responses were required to indicate correctly that no target appeared at the task-relevant level. The targets were ♡ (heart) and ☂ (umbrella). All other objects were distractors.

[4] We adopted a unilateral stimulus presentation (i.e., the divided visual field design), as this design allowed us to examine hemispheric asymmetry for global-local processing. It is important to note, however, that this design does not have a preceding cue, and there were no conditions involving a cue that correctly or incorrectly indicated the visual field in which the hierarchical figure was presented. Thus, unlike the spatial-cueing paradigm, this design did not allow us to examine the directional component of attentional orienting to the LVF and to the RVF.

3.2.4 Procedure

Participants were tested individually in a distraction-free room. Prior to each experiment condition, participants were shown the 18 hierarchical figures to be used in that condition. There were two experiment conditions: global-focused and local-focused. The order of the two experiment conditions was counterbalanced between participants: half of the participants completed the global-focused condition first, followed by the local-focused condition; the other half of the participants completed the local-focused condition first, followed by the global-focused condition. At the beginning of each of the two experiment conditions, participants performed two practice tasks to ensure both understanding and compliance with the task instructions. Feedback regarding accuracy was provided in the practice tasks.

Each of the two experiment conditions (global-focused, local-focused) consisted of 128 trials presented in a random order. Of the 128 trials, 96 trials were target-present trials (32 congruent-target trials, 32 global-target trials, and 32 local-target trials), and 32 were target-absent trials. Hierarchical figures were randomly presented either to the LVF or to the RVF in equal proportions. In 50% of trials, the hierarchical figures were presented to the LVF and in the remaining 50% of trials, the hierarchical figures were presented to the RVF. Each trial began with a central fixation cross (494 ms), followed by a hierarchical figure presented unilaterally either to the LVF or to the RVF (153 ms)[5], and then two post-stimulus masks were presented bilaterally (1000 ms) before the inter-trial interval (1000 ms). No feedback was provided in the experiment conditions.

In the global-focused condition, participants were instructed to focus on the global level and to ignore the local level. They were required to make a 'Yes' response when the target was presented at the global level and to make a 'No' response when the target was not presented at the global level. Therefore, 'Yes' responses were required for the congruent-target trials (i.e., targets at both the global level and the local level) and global-

[5] The stimulus presentation duration was adjusted to synchronise with the refresh rate. The refresh rate of 85 Hz allowed the monitor to run 85 cycles per second, with each cycle lasting 11.76 ms. We adopted a presentation duration of 153 ms, as it allowed the running of 13 complete cycles (i.e., 153 ms/11.76ms = 13 cycles) and thus minimised variation in stimulus presentation duration.

target trials (i.e., target at the global level and distractor at the local level), whereas 'No' responses were required for the local-target trials (i.e., target at the local level and distractor at the global level) and target-absent trials (i.e., distractors at both the global level and the local level). In the local-focused condition, participants were instructed to focus on the local level and to ignore the global level. They were required to make a 'Yes' response when the target was presented at the local level and to make a 'No' response when the target was not presented at the local level. Therefore, 'Yes' responses were required for the congruent-target trials (i.e., targets at both the global level and the local level) and local-target trials (i.e., target at the local level and distractor at the global level), whereas 'No' responses were required for the global-target trials (i.e., target at the global level and distractor at the local level) and target-absent trials (i.e., distractors at both the global level and the local level). See Figure 3.1 for full details. In all practice and experiment trials, participants were asked to press one button on the response box with their right index finger to make a 'Yes' response, and to press a different button on the response box with their right middle finger to make a 'No' response.

3.2.5 Statistical Analysis Plan

Prior to statistical analyses of the incongruent-target figures[6], RT for the correct trials were screened in two steps: (1) correct trials faster than 250 ms were excluded from all statistical analyses—for young participants, no trials were excluded, and for older participants, 0.03% of trials were excluded; (2) correct trials slower than 2.5 SD from the mean were winsorised for each of the repeated-measures conditions for each participant—for young participants, 2.15% of trials were winsorised, and for older participants, 1.59% of trials were winsorised. The repeated-measures conditions were:

1. Yes' responses in the global-focused condition to the global-target figures presented to the LVF and to the RVF;
2. 'Yes' responses in the local-focused condition to the local-target figures presented to the LVF and to the RVF;

[6] See Appendix A for the results from the 'Yes' responses to the congruent-target figures.

3. ‘No’ responses in the global-focused condition to the local-target figures presented to the LVF and to the RVF;
4. ‘No’ responses in the global-focused condition to the target-absent figures presented to the LVF and to the RVF;
5. ‘No’ responses in the local-focused condition to the global-target figures presented to the LVF and to the RVF;
6. ‘No’ responses in the local-focused condition to the target-absent figures presented to the LVF and to the RVF.

For all statistical analyses, linear mixed-effects regression was adopted, in which the RT data for correct trials for each participant were entered as the dependent variable[7]. Participants were entered as random intercepts. While it has been recommended that all within-subjects factors be included as random slopes to capture dependencies in the repeated-measures design (Barr, 2013), we did not include all within-subjects factors in some of the analyses to avoid over-fitting due to singular fits (i.e., the random slopes were too complex to be supported by the data). For all the analyses of the ‘Yes’ responses, Focus Level (global-focused, local-focused) was entered into the random slopes. For all the analyses of the ‘No’ responses, Focus Level (global-focused, local-focused) and Target Type (target at task-irrelevant level, target neither at global nor local level) were entered into the random slopes.

3.2.5.1 Statistical Analyses for Research Question 1: Age-Related Differences in Attentional Orienting for Global-Local Processing. An omnibus analysis was conducted for the ‘No’ Responses. The fixed effects included three within-subjects predictors: Focus Level (global-focused, local-focused), Visual Field (LVF, RVF), and Target Type (target at task-irrelevant level, target neither at global nor local level), and one between-subjects predictor: Age Group (young, older). Significant three-way interactions involving the between-subjects predictor, Age Group, were followed up with additional

[7] Analyses of the accuracy data indicated there was no evidence of a speed-accuracy trade-off (i.e., slower RT across all conditions for both young and older participants was not accompanied by higher accuracy). See Appendix A.

analyses of the 'No' responses for each of the two age groups (young, older). In these additional analyses, the fixed effects included two within-subjects predictors: Focus Level (global-focused, local-focused) and Target Type (target at task-irrelevant level, target neither at global nor local level). The aim of these additional analyses was to respond directly to Research Question 1: *When comparing young with healthy older adults, do healthy older adults demonstrate greater difficulties when a target appeared at the task-irrelevant local level and they were required to disengage their attention from the target at the task-irrelevant local level for the purpose of re-orienting their attention to the task-relevant global level to make a correct 'No' response indicating that no target appeared at the task-relevant level* (as compared to when a target appeared at the task-irrelevant global level and they were required to disengage their attention from the target at the task-irrelevant global level for the purpose of re-orienting their attention to the task-relevant local level to make a correct 'No' response indicating that no target appeared at the task-relevant level)?

The hypothesis here was that age-related difficulties with the directional component of attentional orienting across the left and right visual fields extend to the non-directional component of global-local processing. Specifically, older adults would demonstrate greater difficulties with disengaging attention from a target at the task-irrelevant local level for the purpose of re-orienting their attention to the task-relevant global level, when compared with disengaging attention from a target at the task-irrelevant global level for the purpose of re-orienting their attention to the task-relevant local level. Support for this hypothesis would be indicated by a significant Focus Level (global-focused, local-focused) × Target Type (target at task-irrelevant level, target neither at global nor local level) interaction.

3.2.5.2 Statistical Analyses for Research Question 2: Right-Left Hemispheric Asymmetry for Global-Local Processing. An omnibus analysis was conducted for the 'Yes' Responses. The fixed effects included two within-subject predictors: Focus Level (global-focused, local-focused) and Visual Field (LVF, RVF), and one between-subjects predictor: Age Group (young, older). The aim of the omnibus analyses was to respond directly to Research Question 2: *Would young and older adults demonstrate hemispheric*

asymmetry for global-local processing (i.e., RH-global specialisation and LH-local specialisation) *both for 'Yes' responses (indicating that a target appeared at the task-relevant level) and for 'No' responses (indicating that no target appeared at the task-relevant level) with a Yes/No detection-response mode?* Findings for hemispheric asymmetry would be indicated by significant two-way or three-way interactions involving the within-subjects predictor, Visual Field.

All statistical analyses were carried out in R (version 2024.09.1+394) (R Core Team, 2024), and all fixed effects were deviation coded. The linear mixed-effects regressions were conducted using the "lmer" function in the "lme4" package (Bates et al., 2015). The Type-III analyses of variance (ANOVA) tables with Satterthwaite's method were obtained using the "anova" function in the "lmerTest" package (Kuznetsova et al., 2017). Post hoc pairwise comparisons with Tukey-corrected *p* values and estimated marginal means with confidence intervals were conducted using the "emmeans" function in the "emmeans" package (Lenth, 2024). Post hoc pairwise comparisons reported the mean difference (MD) in milliseconds (ms). Effect size η^2 for main effects and interaction effects was calculated using the "*t*back" approach suggested by Correll et al. (2022), where η^2 is estimated using the formula $\eta^2 = t^2 / (t^2 + df)$. The *t* values and associated *df* (degrees of freedom) were obtained from the model summary using the "summary" function. The effect size *d* for the post hoc pairwise comparisons was computed using the "eff_size" function in the "emmeans" package.[8]

3.3 Results

The omnibus and additional analyses are reported in full in Table 3.2. Results for the interaction effects pertaining to the two research questions are presented in the following sections.

[8] To the best of our knowledge, there is no standard way to compute effect size in linear mixed-effects regressions with an ANOVA-style interpretation (i.e., main effects, interaction effects, and post hoc pairwise comparisons).

3.3.1 Research Question 1: Age-Related Differences in Attentional Orienting for Global-Local Processing

3.3.1.1 'No' Responses: No Target at the Task-Relevant Level. The omnibus analysis for the 'No' responses (see Table 3.2: Panel 2) indicated there was a significant three-way Focus Level (global-focused, local-focused) × Target Type (target at task-irrelevant level, target neither at global nor local level) × Age Group (young, older) interaction. As planned, additional analyses for the 'No' responses for each of the two age groups (young, older) were conducted (see Table 3.2: Panel 3 for young participants and Panel 4 for older participants). A significant Focus Level × Target Type interaction was found for the older participants' responses but not for the young participants. The results for the post hoc pairwise comparisons for older participants were as follows:

1. Target-present at task-irrelevant level: 'No' responses in the global-focused condition to the task-irrelevant local-target figures were significantly slower than 'No' responses in the local-focused condition to the task-irrelevant global-target figures, MD = –34.10 ms, 95% [–61.98, –6.22], SE = 10.85, t = –3.14, p = .009, d = 0.20. These findings indicated worse performance for older participants when the target was presented at the task-irrelevant local level of the hierarchical figure and they were required to disengage attention from the task-irrelevant local level for the purpose of re-orienting attention to the task-relevant global level of the hierarchical figure, as compared to when the target was presented at the task-irrelevant global level of the hierarchical figure and they were required to disengage attention from the task-irrelevant global level for the purpose of re-orienting attention to the task-relevant local level of the hierarchical figure.

2. Target-absent (i.e., target neither at global nor local level): 'No' responses to target-absent figures in the global-focused condition were not significantly different from 'No' responses to target-absent figures in the local-focused condition, MD = –21.13 ms, 95% [–51.54, 9.27], SE = 11.83, t = –1.79, p = .28, d = 0.12. These findings indicated there were no differences in the performance of older participants in the global-focused condition, as compared to the local-

focused condition, when there was no target presented (target neither at global level nor local level of the hierarchical figure).

3. Target-present at task-irrelevant level compared to target-absent (i.e., target neither at global nor local level):

    a. 'No' responses in the global-focused condition to the local-target figures were significantly slower than 'No' responses in the local-focused condition to the target-absent figures, MD = –51.72 ms, 95% CI [–72.68, –30.77], SE = 8.16, t = –6.34, $p < .001$, d = 0.21. These findings indicated worse performance for older participants when the target was presented at the task-irrelevant local level of the hierarchical figure, and they were required to disengage attention from the task-irrelevant local level for the purpose of re-orienting attention to the task-relevant global level of the hierarchical figure, as compared to when there was no target presented (i.e., target neither at task-irrelevant local level nor at task-relevant global level of the hierarchical figure).

    b. 'No' responses in the local-focused condition to the global-target figures were not significantly different from 'No' responses in the local-focused condition to the target-absent figures, MD = 3.51 ms, 95% CI [–17.38, 24.40], SE = 8.13, t = 0.43, p = .97, d = 0.02. These findings indicated there were no differences in the performance of older participants when the target was presented at the task-irrelevant global level of the hierarchical figure, and they were required to disengage attention from the task-irrelevant global level for the purpose of re-orienting attention to the task-relevant local level of the hierarchical figure, as compared to when there was no target presented (i.e., target neither at task-irrelevant global level nor at task-relevant local level of the hierarchical figure). See Figure 3.2 for the estimated marginal means.

Overall, these findings for the older participants indicated support for age-related difficulties with disengaging attention from a target presented at the task-irrelevant level of a hierarchical figure, specifically with disengaging attention from a target presented at the task-irrelevant local level of the hierarchical figure for the purpose of re-orienting attention to the task-relevant global level of the hierarchical figure (as compared to

disengaging attention from a target presented at the task-irrelevant global level of the hierarchical figure for the purpose of re-orienting attention to the local level of the hierarchical figure). Importantly, when disengaging attention was not required because there was no target presented (target neither at global nor local level), there were no age-related differences in task performance between the global-focused condition and the local-focused condition.

3.3.2 Research Question 2: Right-Left Hemispheric Asymmetry for Global-Local Processing

3.3.2.1 'Yes' Responses: Target at the Task-Relevant Level. The omnibus analysis for the 'Yes' responses (see Table 3.2: Panel 1) indicated there were two significant two-way interactions with Visual Field: Focus Level (global-focused, local-focused) × Visual Field (LVF, RVF) interaction and Visual Field (LVF, RVF) × Age Group (young, older) interaction. The three-way Focus Level × Visual Field × Age Group interaction was not significant.

Results for the post hoc pairwise comparisons for the Focus Level × Visual Field interaction for young and older participants were as follows:

1. 'Yes' responses to global-target figures in the LVF/RH ($M_{\text{global-focused-LVF/RH}}$ = 666.79 ms, 95% CI [642.18, 691.39]) were faster than 'Yes' responses to global-target figures in the RVF/LH ($M_{\text{global-focused-RVF/LH}}$ = 712.60 ms, 95% CI [687.80, 737.39]), MD = –45.81 ms, 95% [–63.06, –28.56], SE = 6.72, t = –6.82, p < .001, d = 0.30;
2. 'Yes' responses to local-target figures in the LVF/RH ($M_{\text{local-focused-LVF/RH}}$ = 666.79 ms, 95% CI [642.18, 691.39]) were not significantly different from 'Yes' responses to local-target figures in the RVF/LH ($M_{\text{local-focused-RVF/LH}}$ = 663.29 ms, 95% CI [640.32, 686.26]), MD = –6.41 ms, 95% [–23.22, 10.40], SE = 6.54, t = –0.98, p = .76, d = 0.04. See Figure 3.3 for the estimated marginal means.

Results for the post hoc pairwise comparisons for the Visual Field × Age Group interaction were as follows:

1. Young participants' 'Yes' responses to LVF/RH stimuli ($M_{\text{young-LVF/RH}}$ = 582.02 ms, 95% CI [550.76, 613.28]) were not significantly different from their 'Yes' responses to RVF/LH stimuli ($M_{\text{young-RVF/LH}}$ = 584.17 ms, 95% CI [552.90, 615.44]), MD = –2.15 ms, 95% [–18.35, 14.05], SE = 6.31, t = –0.34, p = .99, d = 0.01;
2. Older participants' 'Yes' responses to LVF/RH stimuli ($M_{\text{older-LVF/RH}}$ = 741.65 ms, 95% CI [709.82, 773.48]) were faster than their 'Yes' responses to RVF/LH stimuli ($M_{\text{older-RVF/LH}}$ = 791.72 ms, 95% CI [759.71, 823.73]), MD = –50.07 ms, 95% [–67.90, –32.24], SE = 6.94, t = –7.21, p < .001, d = 0.33;
3. Young participants' 'Yes' responses to LVF/RH stimuli were faster than older participants' 'Yes' responses to LVF/RH stimuli, MD = –159.63 ms, 95% [–218.11, –101.15], SE = 22.76, t = –7.01, p < .001, d = 1.05;
4. Young participants' 'Yes' responses to RVF/LH stimuli were faster than older participants' 'Yes' responses to RVF/LH stimuli, MD = –157.48 ms, 95% [–215.96, –98.99], SE = 22.77, z = –6.92, p < .001, d = 1.37.

3.3.2.2 'No' Responses: No Target at the Task-Relevant Level. The additional analyses (following the omnibus analysis reported for Research Question 1; see Table 3.2: Panel 3 for young participants and Panel 4 for older participants) for the 'No' responses indicated there was a significant Visual Field (LVF, RVF) × Target Type (target at task-irrelevant level, target neither at global nor local level) interaction for older participants, but not for young participants. There were no other significant interactions with Visual Field, for either the young participants or the older participants. See Figure 3.3 for the estimated marginal means.

Post hoc pairwise comparisons for the significant Visual Field × Target Type interaction for older participants were as follows:

1. 'No' responses to target-*present* figures (i.e., target at task-irrelevant level) were faster in the LVF/RH ($M_{\text{target at task-irrelevant level-LVF/RH}}$ = 773.53 ms, 95% CI [739.93, 807.13]) compared to the RVF/LH ($M_{\text{target at task-irrelevant level-RVF/LH}}$ = 793.99 ms, 95% CI

[760.36, 827.63]), MD = –20.47 ms, 95% [–34.40. –6.53], SE = 5.42, t = –3.77, p < .001, d = 0.12;

2. ‘No’ responses to target-*absent* figures (i.e., target neither at global nor local level) were not significantly different in the LVF/RH ($M_{\text{target neither at global nor local level-LVF/RH}}$ = 762.40 ms, 95% CI [725.11, 799.70]) compared to the RVF/LH($M_{\text{target neither at global nor local level-RVF/LH}}$ = 756.90 ms, 95% CI [719.62, 794.19]), MD = 5.50 ms, 95% [–13.06, 24.06], SE = 7.22, t = 0.76, p = .87, d = 0.03.

Overall, our findings for young and older participants indicated support for RH-global specialisation for the ‘Yes’ responses, but not for the ‘No’ responses. For the ‘Yes’ responses, both age groups demonstrated better performance when a target was presented at the task-relevant global level in the LVF/RH compared to RVF/LH. For young and older participants, there was no support for LH-local specialisation for either the ‘Yes’ or ‘No’ responses. Additionally, our findings indicated that older participants demonstrated overall better performance for stimuli presented to the LVF/RH compared to the RVF/LH, both for ‘Yes’ responses (i.e., when a target was presented at the task-relevant level) and for ‘No’ responses (i.e., when no target was presented at the task-relevant level).

Table 3.2

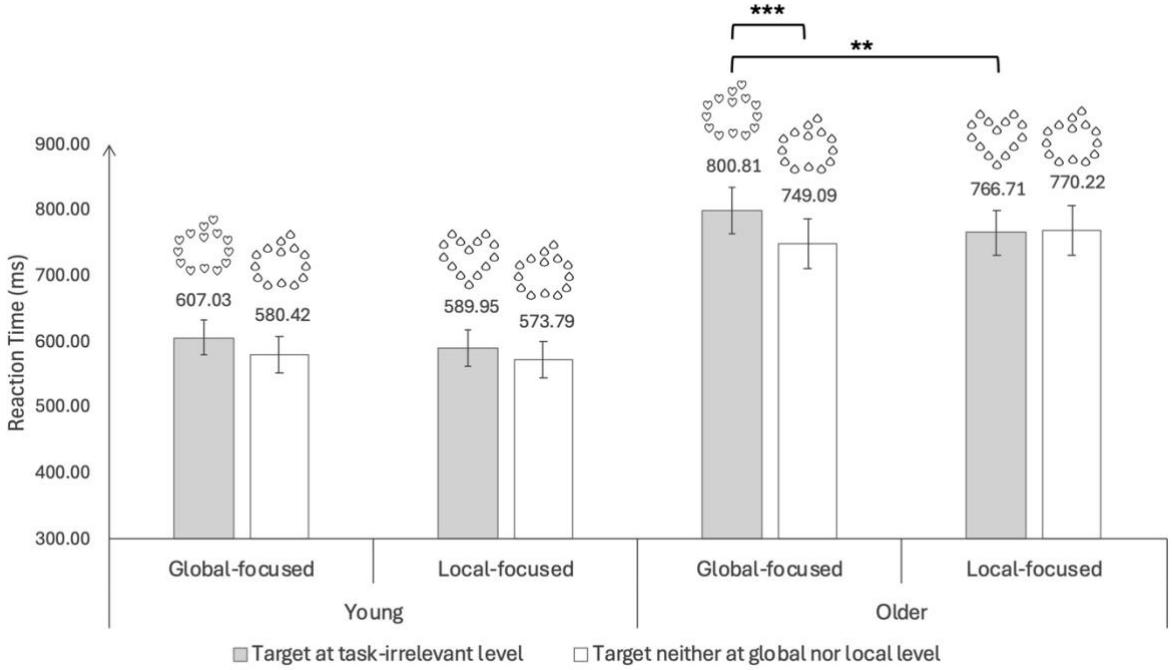
Omnibus and Additional Analyses: Reaction Times for 'Yes' and 'No' Responses

Effects	df_1	df_2	F	p	η^2
1. Omnibus analysis for 'Yes' responses					
Focus Level	1	71.74	17.51	< .001***	.20
Visual Field	1	4157.40	31.02	< .001***	.007
Age Group	1	74.77	67.72	< .001***	.48
Focus Level × Visual Field	1	4156.67	17.65	< .001***	.004
Focus Level × Age Group	1	71.74	3.01	.09	.04
Visual Field × Age Group	1	4157.40	26.12	< .001***	.006
Focus Level × Visual Field × Age Group	1	4156.67	0.74	.39	.0002
2. Omnibus analysis for 'No' responses					
Focus Level	1	77.12	2.59	.11	.03
Visual Field	1	13378.70	1.95	.16	.0001
Target Type	1	72.61	29.91	< .001***	.29
Age Group	1	74.85	68.71	.41	.48
Focus Level × Visual Field	1	13377.57	0.67	< .001***	.0001
Focus Level × Target Type	1	13401.41	38.08	< .001***	.003
Focus Level × Age Group	1	77.12	0.22	.64	.003
Visual Field × Target Type	1	13377.59	7.93	.005**	.0006
Visual Field × Age Group	1	13378.70	2.02	.16	.0002
Target Type × Age Group	1	72.61	0.11	.74	.002
Focus Level × Visual Field × Target Type	1	13377.85	5.18	.02*	.004
Focus Level × Visual Field × Age Group	1	13377.57	0.06	.81	< .0001
Focus Level × Target Type × Age Group	1	13401.41	17.62	< .001***	.001
Visual Field × Target Type × Age Group	1	13377.59	4.27	.04*	.0003
Focus Level × Visual Field × Target Type × Age Group	1	13377.85	0.10	.76	< .0001
3. Additional analysis for 'No' responses for young participants					
Focus Level	1	40.21	5.63	.02*	.01
Visual Field	1	7079.23	0.0005	.98	< .0001
Target Type	1	37.23	18.60	< .001***	.33
Focus Level × Visual Field	1	7078.22	0.26	.61	< .0001
Focus Level × Target Type	1	7080.67	3.10	.08	.0004
Visual Field × Target Type	1	7078.69	0.44	.51	.0001
Focus Level × Visual Field × Target Type	1	7078.86	3.09	.08	.0004
4. Additional analysis for 'No' responses for older participants					
Focus Level	1	38.21	0.39	.53	.01
Visual Field	1	6301.26	2.75	.10	.0004
Target Type	1	35.90	12.68	.001**	.26
Focus Level × Visual Field	1	6301.08	0.39	. 53	.0001
Focus Level × Target Type	1	6319.48	37.20	< .001***	.006
Visual Field × Target Type	1	6300.39	8.26	.004**	.001
Focus Level × Visual Field × Target Type	1	6300.47	2.30	.13	.0004

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

Figure 3.2

Age-Related Differences in Attentional Orienting for Global-Local Processing: Estimated Marginal Means for Focus Level by Target Type Interaction—'No' Responses

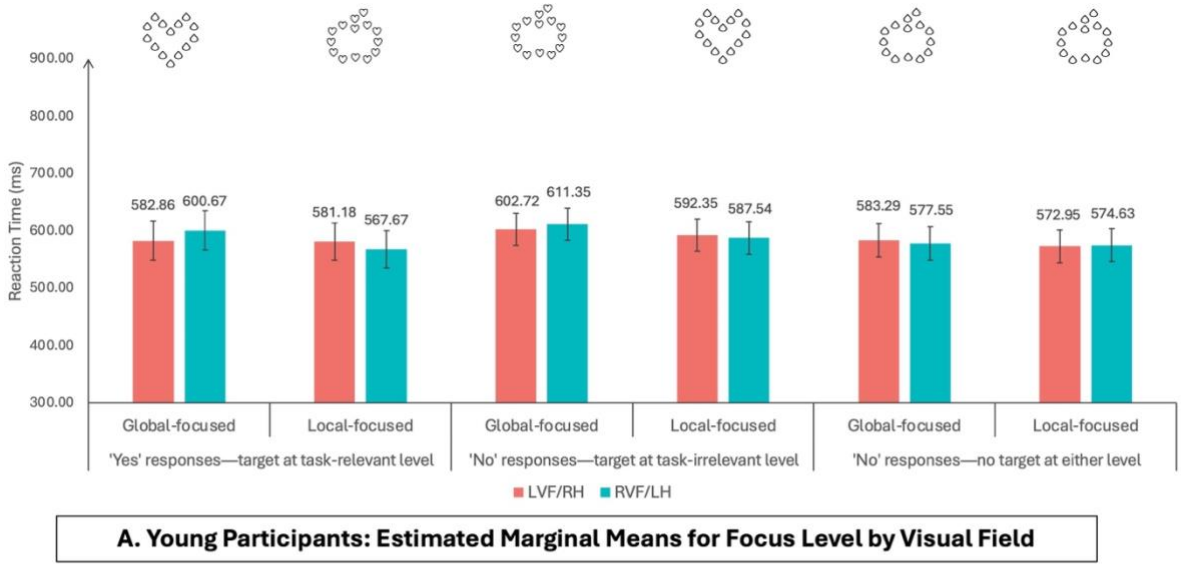


Note. ** $p < .01$; *** $p < .001$. Error bars represent 95% confidence intervals.

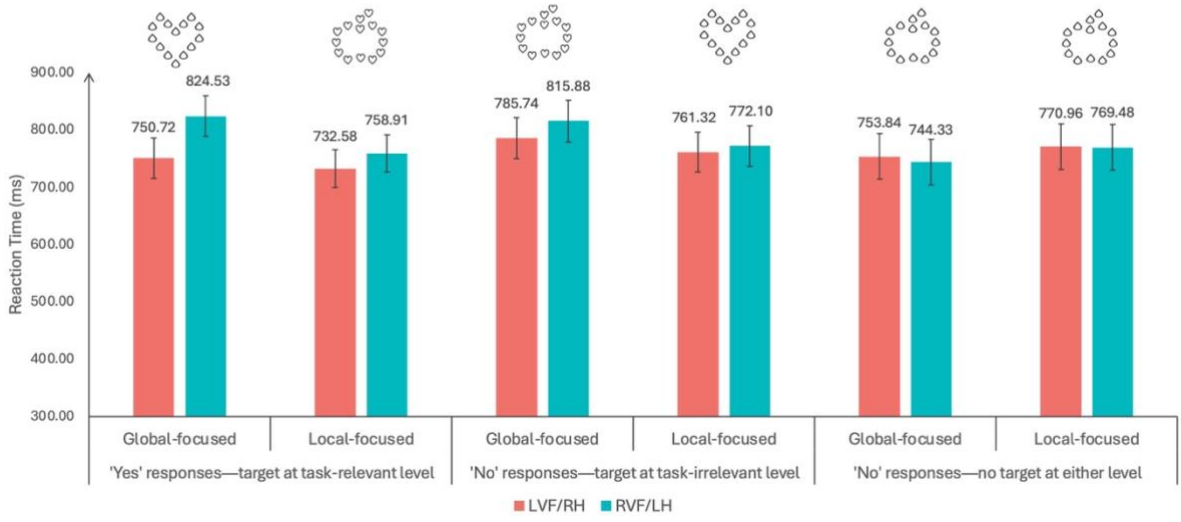
These example hierarchical figures illustrate 'No' responses. The hierarchical figures shown above the grey bars indicate that the target ♡ (heart) was presented either at the task-irrelevant local level in the global-focused condition or at the task-irrelevant global level in the local-focused condition. The hierarchical figures shown above the white bars illustrate that the target ♡ (heart) was presented neither at the global nor the local level. Instead, distractors, either 🍎 (apple) or 💧 (drop), were presented at both the task-relevant level and the task-irrelevant level.

Figure 3.3

Right-Left Hemispheric Asymmetry for Global-Local Processing: Estimated Marginal Means for Focus Level by Visual Field Interaction—'Yes' Responses and 'No' Responses



A. Young Participants: Estimated Marginal Means for Focus Level by Visual Field



B. Older Participants: Estimated Marginal Means for Focus Level by Visual Field

Note. LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere. Error bars represent 95% confidence intervals. An example hierarchical figure is presented in each condition, in which the target was ♡ (heart), and the distractors were either 🍎 (apple) or 💧 (drop). A 'Yes' response indicated that the target ♡ appeared at the task-relevant level. A 'No' response indicated that the target ♡ did not appear at the task-relevant level.

3.4 Discussion

Healthy ageing influences the efficiency of processing global-level information as compared with local-level information—older adults demonstrate age-related worse performance in global processing, whereas local processing remains relatively intact (Chen & Aimola Davies, 2025; Chen et al., 2024). The present study extended this literature by examining whether healthy ageing also influences attentional orienting for global-local processing. Young participants and older participants were tested with Navon's (1977) hierarchical figures, using the focused-attention version of the global-local processing paradigm with a Yes/No detection-response mode.

3.4.1 Age-Related Differences in Attentional Orienting for Global-Local Processing

Two key findings emerged from the 'No' response conditions in relation to our main research question concerning age-related differences in attentional orienting for global-local processing.

The first key finding is that older adults demonstrate worse performance for 'No' responses when the target was presented at the task-irrelevant local level, as compared to the task-irrelevant global level. These findings indicate that older adults demonstrate greater difficulties with disengaging attention from a target presented at the task-irrelevant local level for the purpose of re-orienting attention to the task-relevant global level, as compared to disengaging attention from a target presented at the task-irrelevant global level for the purpose of re-orienting attention to the task-relevant local level. Whereas young participants demonstrate no performance differences between these two 'No' response conditions.

The second key finding is that older adults demonstrate worse performance for 'No' responses when the target was presented at the task-irrelevant local level in the global-focused condition, as compared to when a target was not presented (neither at the global nor local level). In contrast, older adults did not demonstrate performance differences for 'No' responses when the target was presented at the task-irrelevant global level in the local-focused condition, as compared to when a target was not presented (neither at the global nor local level). These findings indicate that the presence of target information at

the task-irrelevant local level may have captured older adults' attention, resulting in difficulties disengaging attention from the task-irrelevant local level and re-orienting attention to the task-relevant global level. In contrast, the presence of target information at the task-irrelevant global level did not appear to capture older adults' attention, thus allowing attention to be disengaged from the task-irrelevant global level and re-oriented to the task-relevant local level.

Taken together, our findings suggest that, in older adults, attention is captured by local-level information, whether or not this information is task-relevant or task-irrelevant. In the global-focused condition, older participants were required to disengage attention from the task-irrelevant local level, which first captured their attention, for the purpose of re-orienting attention to the task-relevant global level (to make a correct 'No' response indicating that no target appeared at the task-relevant level). The findings indicate that the presence of target information at the local level increases the difficulties for older participants to disengage attention from the task-irrelevant local level. These difficulties became evident in the comparison of two of the global-focused conditions: older participants demonstrated slower 'No' responses in the target-present condition, with the target presented at the task-irrelevant local level, as compared to in the target-absent condition, with the target presented neither at the global nor local level.

These findings extend current theoretical understanding of how healthy ageing influences visual attentional processing. Previous studies have established that older adults demonstrate age-related difficulties with processing global-level information compared to young participants, whereas the processing of local-level information remains relatively intact with age (Chen & Aimola Davies, 2025; Chen et al., 2024; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002). The findings from the present study indicate that healthy ageing affects not only the processing of global-level information but also the ability to disengage attention from local-level information for the purpose of re-orienting attention to global-level information. Based on these findings, we propose three components that contribute to these age-related differences in global-local processing: (1) older adults preferentially allocate attention to local-level information rather than global-level information, with their performance when

processing local-level information comparable to that of young adults; (2) older adults demonstrate greater difficulties than young adults with disengaging attention from local-level information when the task demands require that attention is directed to global-level information; (3) older adults demonstrate worse performance than young adults in the processing of global-level information even when attention has been directed to global-level information (see Chen & Aimola Davies, 2025; Chen et al., 2024).

The findings from the present study also extend our current understanding of the right-hemisphere ageing hypothesis, which proposes that RH functions are more vulnerable to ageing than LH functions. Guilbert et al. (2019) used a spatial-cueing paradigm and found that healthy ageing relates to difficulties with the directional component of attentional orienting—age-related greater difficulties with disengaging attention from the RVF for the purpose of re-orienting attention to the LVF (as compared to disengaging attention from the LVF for the purpose of re-orienting attention to the RVF). The findings from the present study build on Guilbert et al.'s findings by demonstrating that healthy ageing also relates to difficulties with the non-directional component of attentional orienting—age-related greater difficulties with disengaging attention from local-level information for the purpose of re-orienting attention to global-level information (as compared to disengaging attention from global-level information for the purpose of re-orienting attention to local-level information). Together, the findings from Guilbert et al. and the present study suggest that healthy ageing influences the RH functions involved in disengaging attention and re-orienting attention, for both the directional (right-to-left side orientation) and the non-directional (local-to-global orientation) components of attentional orienting considered primarily to be RH functions.

We encourage future studies using different experimental paradigms to replicate our findings of age-related difficulties with disengaging attention from local-level information. One approach is to adopt a design similar to the task-switching paradigm, in which the trial sequence includes repeated trials with a target presented at the same processing level for multiple trials, followed by a switch trial with a target presented at the other processing level. Performance differences between the local-repeated trials and the global-switch trials would reflect the switch costs of disengaging attention from

the local level and re-orienting attention to the global level, and performance differences between the global-repeated trials and the local-switch trials would reflect the switch costs of disengaging attention from the global level and re-orienting attention to the local level.

3.4.2 Right-Left Hemispheric Asymmetry for Global-Local Processing

We also investigated hemispheric asymmetry for global-local processing, given that we used a Yes/No detection-response mode (i.e., 'Yes' indicating that a target appeared at the task-relevant level and 'No' indicating that no target appeared at the task-relevant level) whereas previous studies (Chen & Aimola Davies, 2025; Chen et al., 2024; Oken et al., 1999) have used a Go/No-go response mode (i.e., respond when a target appears, do not respond when no target appears). We found support only for RH-global specialisation in both young and older participants, and only for the 'Yes' responses. Specifically, both age groups demonstrated faster 'Yes' responses in the LVF/RH compared to the RVF/LH when a target was presented at the task-relevant global level. There was no support for LH-local specialisation for the 'Yes' responses, and there was also no support for hemispheric asymmetry for global-local processing for the 'No' responses.

Three previous studies (Chen & Aimola Davies, 2025; Chen et al., 2024; Oken et al., 1999) have examined hemispheric asymmetry for global-local processing in both young and older adults, and they reported evidence for RH-global specialisation and LH-local specialisation across the two age groups. These three studies adopted a Go/No-go response mode, in which participants were instructed to respond when a target appeared (i.e., a 'Go' response) and not to respond when no target appeared (i.e., a 'No-go' response). In contrast, the present study adopted a Yes/No detection-response mode, in which participants were instructed to make a 'Yes' response when a target appeared and to make a 'No' response when no target appeared. We suggest that finding evidence of hemispheric asymmetry is more difficult in the Yes/No detection-response mode compared to the Go/No-go response mode, due to the longer RT associated with 'Yes' responses and 'No' responses. These longer RT may arise from two contributing factors: (1) the requirement to choose between two opposing response options ('Yes' *versus* 'No')

increases response selection demands, which can slow response execution compared to one response option in the Go/No-go response mode: (2) 'No' responses may involve additional decision-making time, as a 'No' response is generated following the rejection of a 'Yes' response (Taniguchi et al., 2018).

It is also important to note here that our findings indicated that older participants demonstrated overall faster RT in the LVF/RH compared to RVF/LH for: (1) 'Yes' responses, when a target was presented at the task-relevant level; and (2) 'No' responses, when no target was presented at the task-irrelevant level. These findings of a LVF/RH bias in older participants are unexpected and are in contrast with evidence supporting the right-hemisphere ageing hypothesis. In particular, evidence from a landmark task has suggested that older adults demonstrate a rightward attention bias to the RVF, whereas young adults demonstrate a leftward attention bias to the LVF (Schmitz & Peigneux, 2011). One possible explanation of our unexpected findings relates to task difficulty. The present study involved high task demands, requiring participants to: (1) allocate attention across the two visual fields; (2) coordinate attention between the two opposing response options ('Yes' *versus* 'No'); and (3) re-orient attention back to the task-relevant level when targets were presented at the task-irrelevant level. Older participants experiencing task difficulty may have strategically prioritised attention to one visual field while compromising performance in the other visual field. One factor that may have contributed to this attention bias to the LVF observed in older adults is reading direction. All participants in the present study reported reading at least one language that is written from left to right. Under high task demands, older participants may have relied on a familiar left-to-right reading direction and thus prioritised stimuli presented to the left side of central fixation. Future research is needed to clarify whether reading direction contributes to the attention bias to the LVF observed in older adults.

3.5 Conclusion

To summarise, the present study was the first to examine age-related differences in visual attention that are specific to the non-directional components of attentional orienting. The findings indicate that older adults demonstrate greater difficulties with disengaging attention from local-level information for the purpose of re-orienting attention to global-level information, as compared to disengaging attention from global-level information for the purpose of re-orienting attention to local-level information. These findings extend our current understanding of how healthy ageing influences visual attention across the lifespan. The findings also hold clinical relevance for neuropsychological research, particularly in advancing the assessment of right hemisphere functions in both healthy ageing, and neurological patients following right hemisphere damage.

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Chapter 4 Individual Differences in Hemispheric Asymmetry for Global-Local Processing in Young and Older Adults

Publication Note

The study presented in this chapter has been published as:

Chen, H. & Aimola Davies, A. M. (2025). Individual differences in hemispheric asymmetry for global-local processing in young and older adults. *Laterality*, *30*(2–6), 136–167. https://doi.org/10.1080/1357650X.2025.2577355

Abstract

The two hemispheres of the brain demonstrate functional asymmetry for global-local processing, with global processing specialised in the right hemisphere and local processing specialised in the left hemisphere. Previous research indicates that hemispheric asymmetry remains intact with age, despite older adults demonstrating worse overall performance for global processing. Participants (127 young, 58 older) completed a hierarchical-figures task using a divided visual field design—stimuli presented briefly to the left or right visual field, such that information was initially processed by the contralateral hemisphere. At the group level: (1) young and older participants demonstrated better performance for global hierarchical figures presented to the left visual field (right-hemisphere global specialisation) and for local hierarchical figures presented to the right visual field (left-hemisphere local specialisation); (2) older participants demonstrated worse overall performance only for global hierarchical figures when compared to young participants. At the individual level, while approximately half the participants demonstrated the predicted pattern of hemispheric asymmetry (right-hemisphere global specialisation; left-hemisphere local specialisation), there were

subgroups of participants who demonstrated different patterns. Our findings indicate individual differences in hemispheric asymmetry exist for global-local processing in right-handed participants, and that this may explain the inconsistent findings in group-level studies with small sample sizes.

4.1 Introduction

The two hemispheres of the human brain may appear symmetrical in structure, but they are not functionally equivalent with regard to perceptual, attentional, and cognitive processing. A key area of research on hemispheric asymmetry focuses on functional differences in the visual attentional mechanism of global-local processing. Our visual environment consists of hierarchical structures: a scene with many trees can be perceived as either an entire forest or as individual trees in the forest. Global-local processing is the visual attentional mechanism that directs attention either globally (e.g., to the overall visual scene, such as the forest) or locally (e.g., to the finer elements in the scene, such as the individual trees or even the leaves on a tree).

Levy-Agresti and Sperry (1968) first introduced the concept of hemispheric asymmetry for global-local processing first introduced the concept of hemispheric asymmetry for global-local processing in their work with split-brain patients. The split-brain procedure involves the surgical sectioning of the corpus callosum and other commissures. As a result of this procedure, direct interhemispheric communication between the two hemispheres is disrupted, allowing researchers to examine cognitive processing within one hemisphere while isolating interference from the other hemisphere. Based on neuropsychological assessment results from split-brain patients, Levy-Agresti and Sperry proposed that the right hemisphere (RH) was specialised for Gestalt processing, and the left hemisphere (LH) was specialised for analytical processing. Early studies, primarily based on split-brain patients, provided support for hemispheric asymmetry in global-local processing (e.g., Nebes, 1971, 1972, 1973, 1974).

It was the development of two key methodologies—Navon's (1977) hierarchical figures and the divided visual field design—that provided a standardised behavioural paradigm to examine hemispheric asymmetry for global-local processing in non-clinical

populations. Hierarchical figures feature a large global stimulus made up of several smaller local stimuli (e.g., a large global letter 'H' made up of smaller local letters 'T'). The divided visual field design was introduced by Gazzaniga in the 1960s for split-brain patient studies (Gazzaniga et al., 1962; see Christman, 2016 for a review). The design was based on the logic that stimuli briefly presented to the left visual field (LVF) would be processed first by the RH, and stimuli briefly presented to the right visual field (RVF) would be processed first by the LH (Beaumont, 1983; Bourne, 2006). By presenting hierarchical figures in a divided visual field design, the relative efficiency of the two hemispheres for global processing can be inferred by comparing participants' task performance with global stimuli in the LVF *versus* the RVF, and the relative efficiency of the two hemispheres for local processing can be inferred by comparing participants' task performance with local stimuli in the RVF *versus* the LVF.

Martin (1979) conducted the first behavioural study to examine hemispheric asymmetry for global-local processing in young adults using hierarchical figures and the divided visual field design. The findings revealed that: global stimuli were detected faster and/or more accurately in the LVF compared to the RVF, indicating that the RH was more efficient in processing global information compared to the LH (i.e., RH-global specialisation); local stimuli were detected faster and/or more accurately in the RVF compared to the LVF, indicating that the LH was more efficient in processing local information compared to the RH (i.e., LH-local specialisation). Subsequent behavioural studies have confirmed Martin's findings, providing further reaction time (RT) and/or accuracy evidence for RH-global specialisation and LH-local specialisation in young adults (RT evidence: Brederoo et al., 2019; Chen et al., 2024; Hübner, 1998; Oken et al., 1999; Peterson & Peterson, 2014; Sergent, 1982; Yovel et al., 2001; accuracy evidence: Brederoo et al., 2017; Chen et al., 2024; Peterson & Peterson, 2014). The findings of hemispheric asymmetry for global-local processing have received further support from neuropsychological studies, neuroimaging studies and electrophysiological studies. Neuropsychological studies have demonstrated that patients with lesions to the RH exhibit deficits in global processing, whereas patients with lesions to the LH exhibit deficits in local processing (e.g., Delis et al., 1986; Lamb et al., 1990; Robertson et al., 1988). Neuroimaging studies with healthy young adults have also indicated greater RH

activation for global processing, and greater LH activation for local processing (e.g., Fink et al., 1996; Fink et al., 1997; Martinez et al., 1997). Likewise, electrophysiological studies with healthy young adults have indicated greater amplitudes of event-related potential components for global processing in the RH compared to the LH, and greater amplitudes of event-related potential components for local processing in the LH compared to the RH (e.g., Heinze & Münte, 1993; Heinze et al., 1998; Malinowski et al., 2002; Volberg & Hübner, 2004).

4.1.1 Individual Differences in Hemispheric Asymmetry for Global-Local Processing

Individuals demonstrate differences in functional hemispheric asymmetry, although many of these individual differences have been treated as random errors and largely ignored (Hellige, 1993). While behavioural studies have provided support for the proposal that, at the group level, there is RH-global specialisation and LH-local specialisation (e.g., Brederoo et al., 2017; Chen et al., 2024; Yovel et al., 2001), there has been limited investigation of individual differences in hemispheric asymmetry for global-local processing. Existing behavioural studies regarding individual differences in hemispheric asymmetry for global-local processing have primarily focused on the influence of specific biological or personality factors on the magnitude of this hemispheric asymmetry, such as sex (Hausinger & Pletzer, 2021; also see Harris et al., 2018) and neuroticism (Compton & Weissman, 2002).

A critical gap exists regarding whether the group findings of RH-global specialisation and LH-local specialisation hold at the individual level. Specifically, when using a behavioural paradigm consisting of hierarchical figures and a divided visual field design, it remains unclear whether right-handed individuals demonstrate both the expected hemispheric asymmetry of RH-global specialisation and LH-local specialisation. An investigation of these individual differences could provide insights into the reliability of the behavioural paradigm, as it is currently used to measure hemispheric asymmetry for global-local processing.

4.1.2 Age-Related Changes in Global-Local Processing and Hemispheric Asymmetry for Global-Local Processing in Older Adults

Healthy ageing influences the relative bias for global processing *versus* local processing (i.e., the global-local processing bias). Findings from behavioural studies using hierarchical figures indicate that there is a local-processing bias in older adults, with better performance for local processing compared to global processing (Chen et al., 2024; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002). Further comparisons between young and older adults have revealed that these age-related changes in global-local processing bias are characterised by worse performance for global processing for older adults compared to young adults, whereas performance for local processing remains relatively intact with age (Chen et al., 2024).

The right-hemisphere ageing hypothesis (Albert, 1981; Brown & Jaffe, 1975; Klisz, 1978) has been put forth to explain the local-processing bias in older adults (see Lux et al., 2008; Oken et al., 1999). The proposal is that RH functions (e.g., global processing) are more vulnerable to ageing compared to LH functions (e.g., local processing). Using the divided visual field design with unilateral presentation of the stimulus to the LVF or to the RVF, one approach for examining the right-hemisphere ageing hypothesis has been to compare whether young adults and older adults differ in RH specialisation (Hellige, 1993). For instance, whether the two age groups differ in RH specialisation for global processing (i.e., better performance for global stimuli in the LVF/RH compared to the RVF/LH). To the best of our knowledge, only Oken et al. (1999) and Chen et al. (2024) have employed a divided visual field design to examine age-related changes in hemispheric asymmetry for global-local processing. The findings for the young adults and older adults in these two studies revealed that, although the older adult group did demonstrate a local-processing bias, the young adults and older adults did not differ in hemispheric asymmetry for global-local processing. Both age groups demonstrated RH-global specialisation (i.e., better performance for global stimuli in the LVF/RH compared to the RVF/LH) and LH-local specialisation (i.e., better performance for local stimuli in the RVF/LH compared to LVF/RH). These findings challenge the right-hemisphere ageing hypothesis and instead indicate that hemispheric asymmetry for global processing and

that for local processing remains intact with age. In the older age group, the RH is still more efficient in processing global information, and the LH is still more efficient in processing local information.

There is an outstanding question that requires further investigation regarding the right-hemisphere ageing hypothesis. While previous findings (Oken et al., 1999; Chen et al., 2024) indicated that the older adult group demonstrate intact RH-global specialisation and LH-local specialisation, there may be a subgroup of older adults who do not demonstrate RH-global specialisation. It is essential to determine whether this subgroup of older adults is contributing to the conclusions currently found in the literature about age-related worse performance for global processing.

4.1.3 Present Study

In the present study, we employed a behavioural paradigm with hierarchical figures presented unilaterally (either to the LVF or to the RVF), in a divided visual field design. A divided-attention task was adopted, in which participants were instructed to attend simultaneously to the global and local level of the hierarchical figure in their search for a target. The target could appear either at the global level or at the local level.

The first research question investigated hemispheric asymmetry for global-local processing (i.e., RH-global specialisation and LH-local specialisation) at the group level, for both right-handed young adults and older adults (see Oken et al., 1999). The aim was to provide supporting evidence for the group findings reported in our earlier work (Chen et al., 2024), where we demonstrated RH-global specialisation and LH-local specialisation for older adults, alongside age-related worse performance for global processing and normal performance for local processing (also see Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002).

The second research question concerned hemispheric asymmetry for global-local processing at the individual level. The aim was to investigate the extent to which individual right-handed young adults and individual older adults demonstrated the expected hemispheric asymmetry of RH-global specialisation (i.e., better performance

for global processing in the LVF/RH compared to RVF/LH) and LH-local specialisation (i.e., better performance for local processing in the RVF/LH compared to LVF/RH).

The third research question investigated the right-hemisphere ageing hypothesis at a subgroup level within the older adult group. The aim was to investigate whether the age-related changes in global-local processing for older adults were driven by a subgroup of older adults who exhibited more pronounced age-related changes in RH function and thus did not demonstrate RH-global specialisation.

4.2 Methods

4.2.1 Participants

A total of 197 participants were recruited for this study: 133 young participants and 64 older participants. All participants self-reported being of 100% European ancestry. Young participants were students from the Australian National University and students from the University of Oxford. Older participants were recruited from the University of the Third Age and the broader community in Canberra. Participants were excluded from statistical analyses if they did not meet the following five inclusion criteria:

1. Right-handed, based on the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were considered to be right-handed if their laterality scores were higher than + 40.00. Two young participants and four older participants scored lower than this laterality score cut-off and were excluded from all statistical analyses.
2. Normal or corrected-to-normal vision, as indicated by in-laboratory testing with a Snellen chart (Snellen, 1868). No young or older participant was excluded.
3. No history of self-reported neurological impairments. No young or older participant was excluded.
4. No evidence of cognitive impairment in older participants, as assessed by the Montreal Cognitive Assessment (MoCA; Nasreddine, 2005), with a score of 24 or greater indicating intact cognitive functioning (see Pugh et al., 2018; Thomann et

al., 2020). One older participant scored lower than this MoCA score cut-off and was excluded from all statistical analyses.

5. Overall accuracy on the target-absent trials for the hierarchical-figures task of 80% or greater. No response was required for these trials, as no target was presented (see Apparatus, Stimuli, and Procedure). A response to a target-absent trial indicates the participant either did not discriminate targets from distractors or tended to respond quickly but with low accuracy. Four young participants and one older participant scored lower than this accuracy cut-off and were excluded from all statistical analyses.

The final statistical analyses included 127 young participants and 58 older participants. See Table 4.1 for full demographic details. Power analyses using G*Power 3.1 were conducted for the analysis of variance (ANOVA) addressing the first research question concerning hemispheric asymmetry for global-local processing at the group level (see Results, Part 1). These power analyses (power = 90%, α = .05, and *f* = .25) indicated that a minimal sample size of 30 participants in each of the two age groups was required to detect a significant within-subjects two-way interaction (i.e., the Level × Visual Field interaction) that would provide support for hemispheric asymmetry for global-local processing.[1] With the actual sample size of 127 young participants and 58 older participants, sensitivity analyses using G*Power 3.1 (power = 90%, α = .05) were conducted: (1) for the chi-square tests, to address the second research question concerning hemispheric asymmetry for global-local processing at the individual level

[1] The medium effect size of *f* = .25 was chosen based on a review of previous behavioural studies that reported a significant Level × Visual Field interaction in reaction time data and provided *F* statistics from which effect sizes could be calculated. These effect size values, ranked from smallest to largest, were: *f* = .26 (McKone et al., 2010, p. 1544); *f* = .30 (Peterson & Peterson, 2014, p. 514); *f* = .42 (Brederoo et al., 2019, p. 2); *f* = .59 (Oken et al., 1999, p. 79); *f* = .68 (Martinez et al., 1997, p. 1688); *f* = .69 (Martin, 1979, p. 36); *f* = 1.71 (Hübner et al., 2007, p. 416). McKone et al. (2010) reported the smallest effect size of *f* = .26 in young adults, and they used a divided-attention task that was very similar to the design in the present study. Of these studies, Oken et al. (1999) was the only study in which older adults were tested, but they used a focused-attention task. Given these considerations, we opted for a medium effect size of *f* = .25, which was slightly smaller than the effect size of *f* = .26 from McKone et al. Choosing this smaller effect size meant that we required a larger sample size for each of the two groups of participants (young and older) to achieve the same level of statistical power.

(see Results, Part 2); (2) for the ANOVA, to address the third research question concerning the right-hemisphere ageing hypothesis at a subgroup level within the older adult group (see Results, Part 3). The sensitivity analyses for the second research question indicated a minimal detectable effect for the chi-square tests: ϕ = .29 for young participants and ϕ = .43 for older participants. The sensitivity analyses for the third research question indicated that a minimal detectable effect of *f* = .30 for the significant two-way interaction (Level × Older Subgroups) would provide evidence of a difference in global-local processing across the four hemispheric asymmetry subgroups in the older age group.[2]

Table 4.1

Demographic Information and Task Accuracy for Young and Older Participants Included in the Statistical Analyses

Demographic Information and Task Accuracy	Young participants	Older participants
N	127	58
Female (*n*, %)	70, 55.12%	39, 67.24%
Male (*n*, %)	57, 44.88%	19, 32.76%
Age		
M	21.68	72.00
SD	2.79	7.30
Range	18–30	57–88
MoCA scoring (*M*, SD)	-	27.56, 1.61
Experimenter (*n*, %) [a]		
1	47, 37.01%	-
2	36, 28.35%	-
3	17, 13.39%	24, 41.37%
4	27, 21.26%	34, 58.62%
Task accuracy		
Target-absent trials	97.23%	95.62%
Global-target trials	98.43%	87.16%
Local-target trials	95.92%	95.42%

Note. [a] Data collection was conducted across two locations by four experimenters. Experimenter 1 recruited young participants studying at the University of Oxford. Experimenter 2 recruited young participants studying at the Australian National University. Experimenters 3 and 4 recruited young participants studying at the Australian National University and older participants from the local Canberra community.

[2] Given that the sample sizes were unequal across the four hemispheric asymmetry subgroups in the older age group (30, 8, 11, and 9 older participants, respectively), we used the harmonic mean as the sample size per subgroup (Field et al., 2012). The harmonic mean was calculated as $n = \frac{4}{\frac{1}{30}+\frac{1}{8}+\frac{1}{11}+\frac{1}{9}} \approx 11$, which resulted in a total sample size of 44 participants for the sensitivity analyses conducted for the third research question.

All participants provided written consent prior to participation in the study and received monetary compensation (or course credit for eligible young participants). The study was approved by the Human Research Ethics Committees at the Australian National University (Protocol: 2013/605 and 2019/795) and the University of Oxford (Protocol: 2010/87). A subset of the participants in the present study was previously reported in Chen et al. (2024).

4.2.2 Apparatus, Stimuli, and Procedure

Participants were tested individually in a distraction-free room. The experiment was presented on a desktop monitor. A forehead-and-chin rest was used to maintain a constant eye-to-screen viewing distance for each participant. Reaction times (RT) and accuracy were recorded using a response pad. See Table 4.2 for apparatus details.

Table 4.2

Apparatus and Experiment Design

Apparatus and experiment design	Experimenter 1	Experimenter 2	Experimenter 3	Experimenter 4
Apparatus				
Display size	17 inches	18 inches	18 inches	27 inches
Resolution	1024 × 768	1280 × 1024	1280 × 1024	2560 × 1440
Frequency	75 Hz	85 Hz	85 Hz	60 Hz
Viewing distance	50 cm	57 cm	50 cm	57 cm
Programming software	E-Prime 2.0	E-Prime 2.0	E-Prime 2.0	Inquisit 6.2.1
Response pad	Chronos PST-100430	Chronos PST-100430	Chronos PST-100430	Cedrus RB-844
Stimuli				
Targets	H, T	S, T	S, T	S, T
Distractors	D, E, U, V	C, D, K, L, U, V	C, D, K, L, U, V	C, D, K, L, U, V
Presentation duration				
Fixation cross	1000 ms	500 ms	500 ms	500 ms
Hierarchical figure	150 ms	150 ms	150 ms	150 ms
Post-stimulus masks	1500 ms	1000 ms	1000 ms	1000 ms
Inter-trial interval	-	1000 ms	1000 ms	1000 ms
N of trials				
Global-target figure	64	32	48	32
Local-target figure	64	32	48	32
Target-absent figure	128	64	96	64

The hierarchical figures were presented in black against a white background. The hierarchical figures were large letters (size = 2.30° × 3.08°–3.90°) composed of seven to 14 small local letters (size = 0.40° × 0.50°). There were two types of letters: targets and distractors. See Table 4.2 for details of the letter stimuli. In each hierarchical figure, targets were either presented (target-present hierarchical figures) or absent (target-absent hierarchical figures). There were two types of target-present hierarchical figures: global-target figures (one target appeared at the global level and one distractor appeared at the local level) and local-target figures (one target appeared at the local level and one distractor appeared at the global level). The target-absent figures were made up of two different distractors (one distractor appeared at the global level and one distractor appeared at the local level).

Participants were familiarised with the hierarchical figures to be used in the task before completing two practice blocks. Feedback about accuracy was provided in the practice blocks to ensure participants' understanding and compliance with the task instructions. In the experiment block, each trial began with a central fixation cross, followed by a hierarchical figure presented unilaterally either to the LVF or to the RVF, and then two post-stimulus masks were presented bilaterally to both the LVF and the RVF. All trials were presented in a randomised order, with the hierarchical figures randomly presented either to the LVF or RVF in equal proportions. The medial edges of the hierarchical figures were positioned 0.50° to the left or to the right of the central fixation cross. Participants were instructed to focus on the central fixation cross, to respond to the targets as quickly and as accurately as possible, and to press a button on a response pad with their right index finger when they saw a target appear either at the global level or local level. They were also instructed not to respond if a target did not appear at either the global level or the local level. Feedback about accuracy was not provided in the experiment block. See Table 4.2 for details of the experiment design.

4.2.3 Statistical Analysis Plan

Prior to statistical analyses, RT for correct trials were screened in two steps. First, trials faster than 250 ms were excluded, resulting in 0.02% of trials in young participants

and 0.10% of trials in older participants being excluded from all statistical analyses. Next, trials slower than 2.5 SD from the mean were winsorised for each of the four repeated-measures conditions in each participant: global target in the LVF; global target in the RVF; local target in the LVF; local target in the RVF. This step resulted in 2.49% of trials in young participants and 2.25% of trials in older participants being winsorised.

Data preparation and screening prior to statistical analyses were conducted in R Studio (version 2024.09.1+394). The statistical analyses were conducted in JASP (version 0.19.2 Apple Silicon). The R syntax for the analyses conducted in JASP and R Studio is available in our open-access R script (https://osf.io/fcymn).The statistical analyses comprised of three parts, and Bayes factors were computed for the analyses in Parts 2 and 3:

- Part 1, 'Age-Group Differences in Hemispheric Asymmetry for Global-Local Processing';
- Part 2, 'Individual-Level Differences in Hemispheric Asymmetry for Global-Local Processing';
- Part 3, 'Age-Related Changes in Global-Local Processing at the Subgroup Level'.

Part 1 was a group analysis that examined whether there were age-related changes in global-local processing, and whether young and older participants demonstrated hemispheric asymmetry for global-local processing. For all analyses conducted in Part 1, the dependent variable was average RT of correct responses to each of the four repeated-measures conditions: global target in the LVF; global target in the RVF; local target in the LVF; local target in the RVF. An omnibus mixed-design analysis of variance (ANOVA)[3] was

[3] We conducted a linear mixed-effects model (equivalent to the omnibus ANOVA) to confirm that minor differences in the experiment design across the four experimenters did not influence the overall results. The independent variables and dependent variable entered in the linear mixed-effects model were identical to those for the omnibus ANOVA. The random intercepts included two cluster factors of Participants and Experimenters. The random slopes included one within-subjects factor of Level (global, local), as the within-subjects factor of Visual Field (LVF, RVF) was excluded from the random slopes to avoid over-fitting due to singular fits (i.e., the random slopes were too complex to be supported by the data). The results of the linear mixed-effects model were consistent with the results of the omnibus ANOVA (see Appendix B). We opted to report the results of the omnibus ANOVA, because the effect sizes derived from the linear

first conducted. The independent variables included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF), and one between-subjects predictor: Age Group (young, older). The aim of this omnibus ANOVA was to examine the research question regarding age-related changes in global-local processing, which would be indicated by a significant two-way interaction between Level (global, local) and Age Group (young, older). Two follow-up repeated-measures ANOVAs were conducted for each of the two age groups. The independent variables included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF). The aim of these follow-up analyses was to examine the research question regarding hemispheric asymmetry for global-local processing in young and older adults. Hemispheric asymmetry for global-local processing would be indicated by two contrasts in the post hoc pairwise comparisons for a significant two-way interaction between Level (global, local) and Visual Field (LVF, RVF). RH-global specialisation would be indicated by significantly faster performance in the detection of global targets presented in the LVF/RH compared to the RVF/LH, and LH-local specialisation would be indicated by significantly faster performance in the detection of local targets presented in the RVF/LH compared to the LVF/RH (Brederoo et al., 2017; Hübner, 1998; Martin, 1979; Sergent, 1982; Van Kleeck, 1989; Yovel et al., 2001). The *p* values were Bonferroni-corrected for the post-hoc pairwise comparisons conducted in Part 1.[4]

Part 2 examined whether individual young and older participants demonstrated both RH-global specialisation and LH-local specialisation. In each age group, participants were categorised based on whether their RT was faster in the LVF or in the

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mixed-effects model are not directly comparable to the conventional effect size measures, such as η_p^2 and Cohen's *d*.

[4] In Part 1, to examine whether sex influenced the group-level findings, we included the between-subjects factor Sex in the omnibus and follow-up ANOVAs. Overall, the results indicated no sex differences in task performance. First, there were no sex differences in hemispheric asymmetry for global-local processing in either young participants or older participants. Second, sex did not modulate the age-related local-processing bias. See Appendix B for the analyses and discussion regarding sex differences in hemispheric asymmetry for global-local processing. We are grateful to the reviewer for suggesting we examine potential sex differences, and we agree that future research with larger and more balanced sample sizes is warranted to examine systematically whether there are sex differences in hemispheric asymmetry for global-local processing.

RVF for each of the two processing levels (global, local). For the global level, participants were categorised into two subgroups:

1. Participants who detected the global targets faster in the LVF compared to the RVF ($RT_{global\text{-}LVF} < RT_{global\text{-}RVF}$);
2. Participants who detected the global targets faster in the RVF compared to the LVF ($RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$).

For the local level, participants were categorised into two subgroups:

1. Participants who detected the local targets faster in the RVF compared to the LVF ($RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$);
2. Participants who detected the local targets faster in the LVF compared to the RVF ($RT_{local\text{-}LVF} < RT_{local\text{-}RVF}$).

This categorisation for the global level and the local level led to a 2 × 2 contingency table of the four different hemispheric asymmetry subgroups for each of the two age groups:

1. Participants who demonstrated both RH-global specialisation ($RT_{global\text{-}LVF} < RT_{global\text{-}RVF}$) and LH-local specialisation ($RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$);
2. Participants who demonstrated an overall LVF/RH advantage ($RT_{global\text{-}LVF} < RT_{global\text{-}RVF}$) and ($RT_{local\text{-}LVF} < RT_{local\text{-}RVF}$);
3. Participants who demonstrated an overall RVF/LH advantage ($RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$) and ($RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$);
4. Participants who demonstrated a reversed hemispheric asymmetry—RH-*local* specialisation ($RT_{local\text{-}LVF} < RT_{local\text{-}RVF}$) and LH-*global* specialisation ($RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$).

A chi-square test was conducted to examine whether there were differences in the percentage of participants in the 2 × 2 contingency table (i.e., the four hemispheric asymmetry subgroups) for each of the two age groups. This analysis addressed the second research question by testing the extent to which participants in each of the two

age groups demonstrated the combination of RH-global specialisation and LH-local specialisation (i.e., Subgroup 1).

Part 3 included a subgroup analysis that examined whether the local-processing bias previously observed in older adult groups was driven by the subgroup of older participants who did not demonstrate RH-global specialisation (i.e., the subgroup of older participants who demonstrated an overall RVF/LH advantage: $RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$). A mixed-design ANOVA was conducted for older participants only. The independent variables included one within-subjects predictor: Level (global, local), and one between-subjects predictor: Older Subgroups (both RH-global specialisation and LH-local specialisation, overall LVF/RH advantage, overall RVF/LH advantage, reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation). The dependent variable was the average RT of correct responses for the two repeated-measures conditions: global-target stimuli and local-target stimuli (averaging across the visual field of presentation). A significant two-way interaction, Level (global, local) × Older Subgroups (both RH-global specialisation and LH-local specialisation, overall LVF/RH advantage, overall RVF/LH advantage, reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation) would indicate differences in relative processing efficiency for global processing *versus* local processing across the four hemispheric asymmetry subgroups in the older age group. We predicted that the older subgroup with an overall RVF/LH advantage would demonstrate worse performance for global processing as compared to the other subgroups, reflecting RH's reduced efficiency in global processing in the RH.

4.3 Results

4.3.1 Part 1. Age-Group Differences in Hemispheric Asymmetry for Global-Local Processing

An omnibus ANOVA was conducted to investigate the age-related changes in global-local processing. The results revealed that there were significant main effects for Level ($F(1, 183) = 89.32$, $p < .001$, $\eta_p^2 = .33$) and Age Group ($F(1, 183) = 7.95$, $p = .005$, $\eta_p^2 = .04$), but there were no significant main effects for Visual Field ($F(1, 183) = 0.22$, $p = .64$,

η_p^2 = .001). There was a significant Level × Age Group interaction (F(1, 183) = 109.52, p < .001, η_p^2 = .37), indicating there were age differences in global-local processing. There was a significant Level × Visual Field interaction (F(1, 183) = 89.71, p < .001, η_p^2 = .33), but there was no significant Visual Field × Age Group interaction (F(1, 183) = 0.41, p = .52, η_p^2 = .002) nor a significant Level × Visual Field × Age Group interaction (F(1, 183) = 0.21, p = .65, η_p^2 = .001). These results indicated that although there were RT differences in detecting the global targets and local targets in the LVF/RH and RVF/LH, there were no age-related differences in hemispheric asymmetry. Results for all interaction effects relevant to the age-related changes in global-local processing and hemispheric asymmetry for global-local processing are presented below.

Post hoc pairwise comparisons for the significant Level × Age Group interaction in the omnibus ANOVA indicated that: (1) young participants demonstrated no RT differences in detecting the global targets and the local targets, whereas older participants were faster in detecting the local targets compared to the global targets; (2) young participants were faster in detecting the global targets compared to older participants, whereas there were no RT differences between young participants and older participants in detecting the local targets. See Table 4.3 for the statistics of the age differences in global-local processing, and Figure 4.1A for the estimated marginal means.

As planned, two follow-up ANOVAs were conducted for each of the two age groups to investigate hemispheric asymmetry for global-local processing. For young participants, there was a significant Level × Visual Field interaction (F(1, 126) = 80.18, p < .001, η_p^2 = .39), but there was no significant main effect for Level (F(1, 126) = 1.10, p = .30, η_p^2 = .01) or Visual Field (F(1, 126) = 1.15, p = .29, η_p^2 = .01). Post hoc pairwise comparisons for the significant interaction indicated that (1) young participants were faster in detecting the global targets in the LVF/RH compared to the RVF/LH; (2) young participants were faster in detecting the local targets in the RVF/LH compared to the LVF/RH.

For older participants, there was a significant main effect for Level, (F(1, 57) = 92.69, p < .001, η_p^2 = .62), but the main effect for Visual Field was not significant (F(1, 57) = 0.008, p = .93, η_p^2 < .001). The significant main effect for Level indicated that older participants

were faster in detecting the local targets (*M* = 519.38 ms, 95% CI [497.18, 541.59]) compared to the global targets (*M* = 627.97 ms, 95% CI [605.77, 650.17]). There was also a significant Level × Visual Field interaction ($F(1, 57) = 25.22$, $p < .001$, $\eta_p^2 = .31$). Post hoc pairwise comparisons for the significant interaction indicated that (1) older participants were faster in detecting the global targets in the LVF/RH compared to the RVF/LH; (2) older participants were faster in detecting the local targets in the RVF/LH compared to the LVF/RH. See Table 4.3 for the statistics of hemispheric asymmetry for global-local processing in young participants and older participants, and Figure 4.1B and Figure 4.1C for the estimated marginal means.

Table 4.3

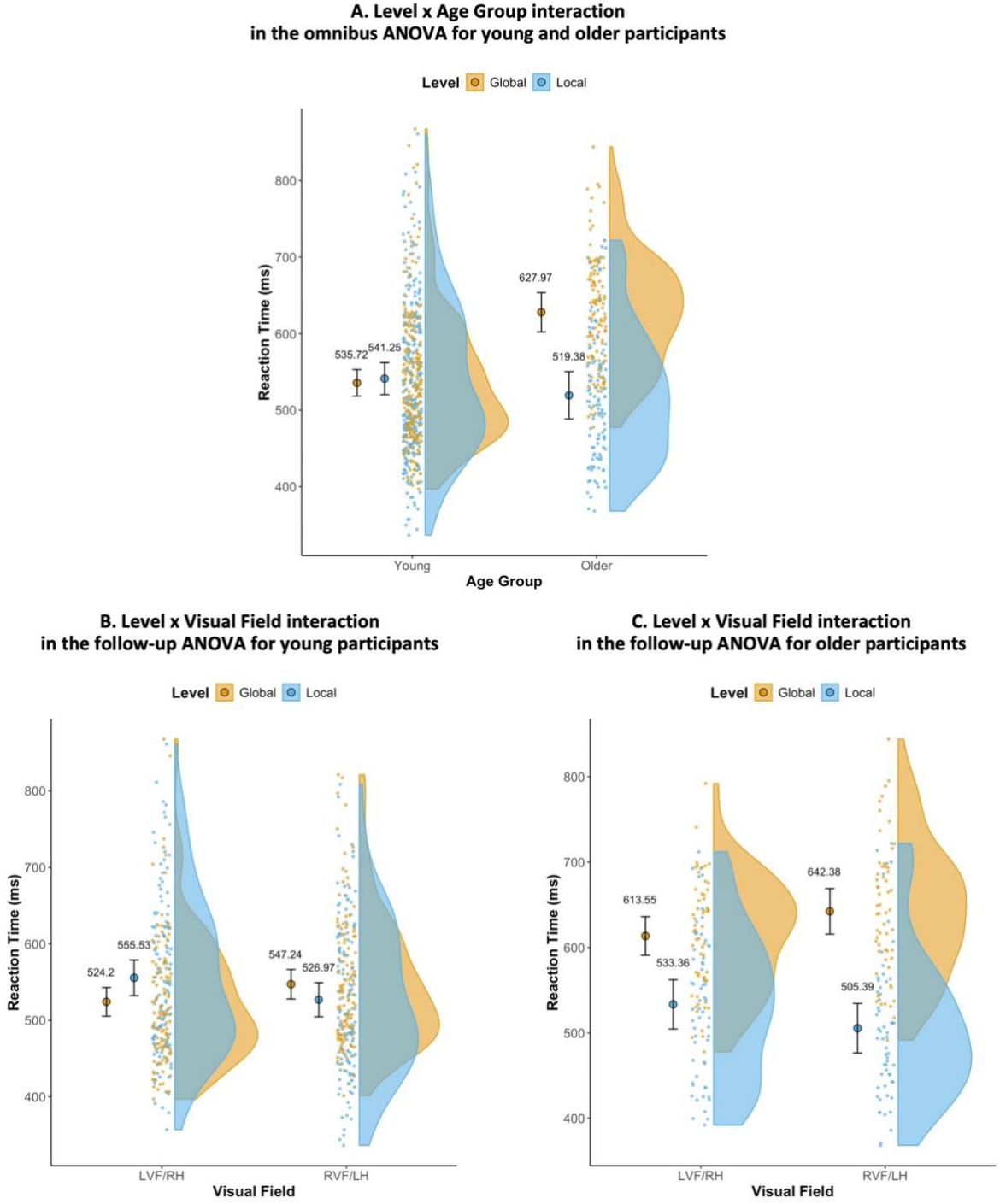
Post-Hoc Pairwise Comparisons for the Level × Age Group Interaction in the Omnibus ANOVA for Young and Older Participants and the Level × Visual Field Interaction in the Follow-Up ANOVA for Each of the Two Age Groups

Contrasts	MD, 95% CI	SE	*df*	*t*	p_{bonf}	*d*, 95% CI
Level × Age Group interaction in the omnibus ANOVA for young and older participants						
Young: global – local	–5.53, [–21.82, 10.76]	6.11	183	–0.91	1.00	–0.06, [–0.25, 1.12]
Older: global – local	108.59, [84.49, 132.69]	9.04	183	12.02	< .001***	1.22, [0.90, 1.54]
Global: young – older	–92.25, [–125.06, –59.43]	12.30	183	–7.50	< .001***	–1.03, [–1.43, –0.64]
Local: young – older	21.88, [–17.65, 61.40]	14.82	183	1.48	.85	0.25, [–0.20, 0.69]
Level × Visual Field interaction in the follow-up ANOVA for young participants						
Global: LVF/RH – RVF/LH	–23.05, [–31.38, –14.72]	3.11	126	–7.52	< .001***	–0.25, [–0.35, –0.15]
Local: LVF/RH – RVF/LH	28.57, [16.51, 40.62]	4.50	126	6.35	< .001***	0.31, [0.17, 0.45]
Level × Visual Field interaction in the follow-up ANOVA for older participants						
Global: LVF/RH – RVF/LH	–28.83, [–52.33, –5.33]	7.41	57	–3.27	.01*	–0.36, [–0.67, –0.05]
Local: LVF/RH – RVF/LH	27.97, [11.56, 44.38]	6.00	57	4.66	< .001***	0.35, [0.13, 0.58]

Note. *$p < .05$; ***$p < .001$; MD = mean differences (ms); p_{bonf} = Bonferroni-corrected *p* values; *d* = Cohen's *d*; LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere.

Figure 4.1

Estimated Marginal Means for the Level × Age Group Interaction in the Omnibus ANOVA for Young and Older Participants and the Level × Visual Field Interaction in the Follow-Up ANOVA for Each of the Two Age Groups



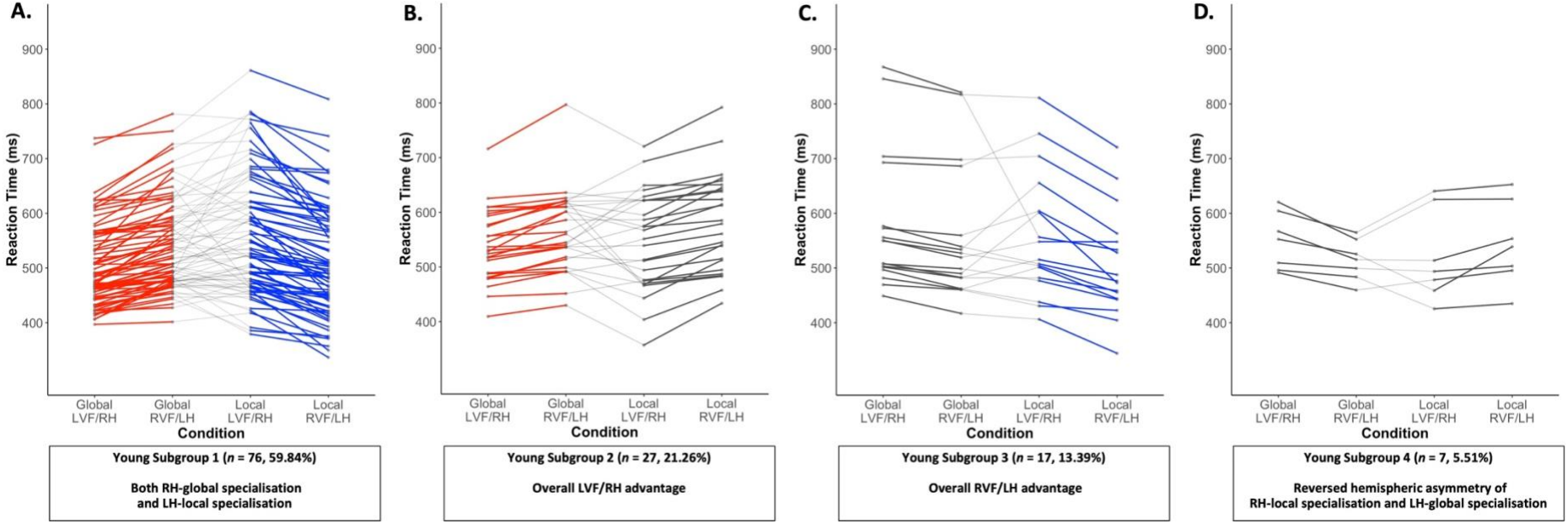
Note. LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere. Error bars represent Bonferroni-corrected 95% confidence intervals, and small dots represent data for each participant.

4.3.2 Part 2. Individual-Level Differences in Hemispheric Asymmetry for Global-Local Processing

As planned, participants in each of the two age groups were categorised into four different hemispheric-asymmetry subgroups: (1) participants who demonstrated both RH-global specialisation and LH-local specialisation (i.e., $RT_{global\text{-}LVF} < RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$); (2) participants who demonstrated an overall LVF/RH advantage (i.e., $RT_{global\text{-}LVF} < RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} < RT_{local\text{-}RVF}$); (3) participants who demonstrated an overall RVF/LH advantage (i.e., $RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$); (4) participants who demonstrated a reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation (i.e., $RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} < RT_{local\text{-}RVF}$). The chi-square tests indicated that, within each age group, participants were not significantly more likely to be in Subgroup 1 (both RH-global specialisation and LH-local specialisation) compared to the other three subgroups (young: $\chi^2(1, N = 127) = 0.09$, $p = .77$, $\phi = -.03$, $BF_{01} = 3.84$; older: $\chi^2(1, N = 58) = 3.63$, $p = .06$, $\phi = -.25$, $BF_{10} = 1.73$). The Bayes factors indicated that: (1) for young participants, the data were 3.84 times more likely to support H_0 compared to H_1, providing moderate evidence against the finding that young participants were more likely to be in Subgroup 1 compared to the three other young subgroups; (2) for older participants, the data were 1.73 times more likely to support H_1 compared to H_0, providing inconclusive evidence as to whether older participants were more likely to be in Subgroup 1 compared to the other three older subgroups. See Figure 4.2 and Figure 4.3 for the illustration of individual differences in hemispheric asymmetry for global-local processing for young participants and older participants, respectively.

Figure 4.2

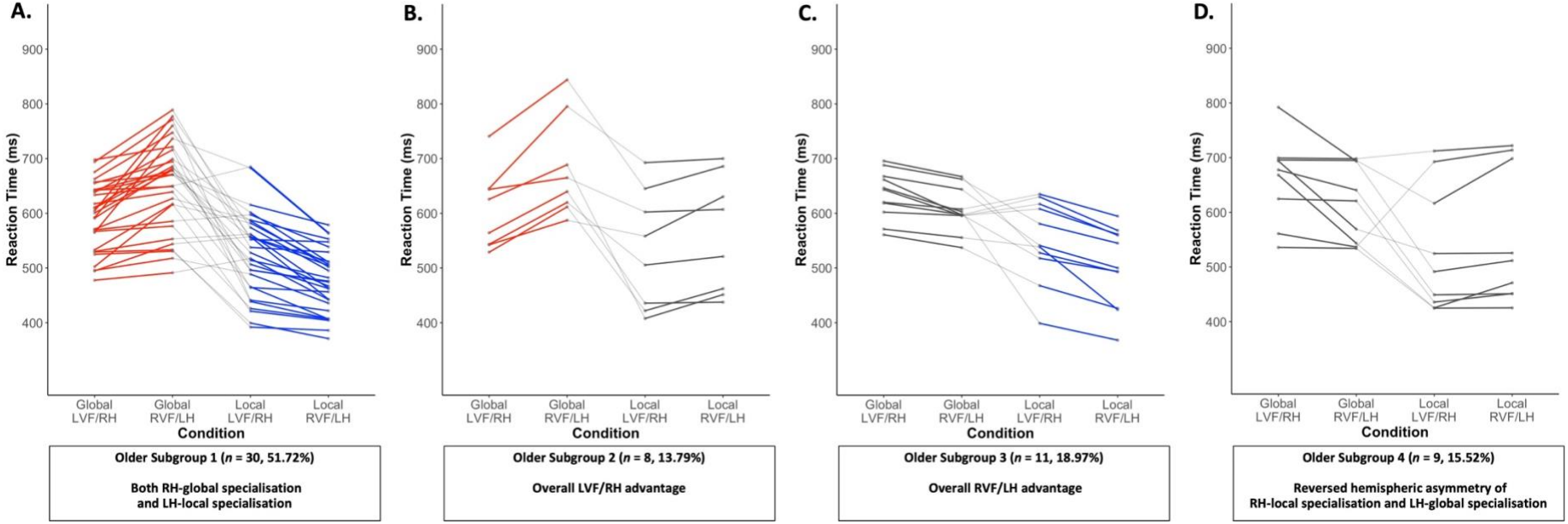
Individual Differences in Hemispheric Asymmetry for Global-Local Processing in Young Participants



Note. A total of 127 young participants were categorised into four hemispheric asymmetry subgroups. Panel A presents Young Subgroup 1, who demonstrated both RH-global specialisation and LH-local specialisation. Panel B presents Young Subgroup 2, who demonstrated an overall LVF/RH advantage. Panel C presents Young Subgroup 3, who demonstrated an overall RVF/LH advantage. Panel D presents Young Subgroup 4, who demonstrated reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation. In each panel, small dots represent the data of each young participant across the four repeated-measures conditions: global targets in the LVF/RH, global targets in the RVF/LH, local targets in the LVF/RH, and local targets in the RVF/LH. Data from the same participant are connected with pale grey lines. Red lines represent participants who demonstrated faster RT in detecting global stimuli presented in the LVF/RH compared to RVF/LH (e.g., RH-global specialisation). Blue lines represent participants who demonstrated faster RT in detecting local stimuli presented in the RVF/LH compared to LVF/RH (e.g., LH-local specialisation).

Figure 4.3

Individual Differences in Hemispheric Asymmetry for Global-Local Processing in Older Participants



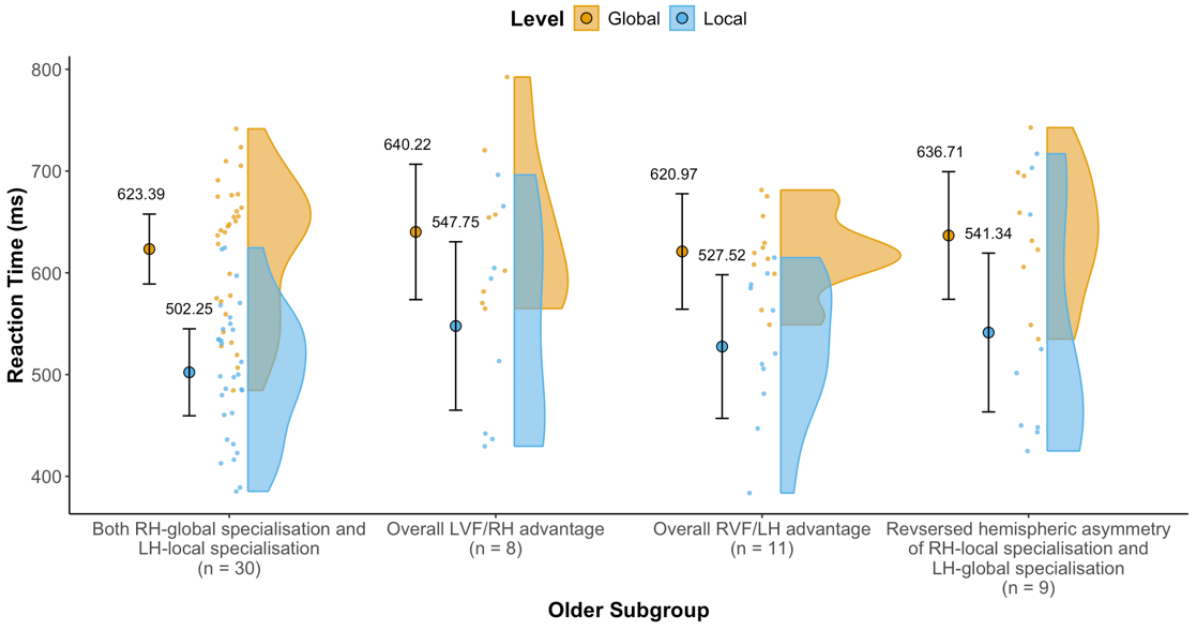
Note. A total of 58 older participants were categorised into four hemispheric asymmetry subgroups. Panel A presents Older Subgroup 1, who demonstrated both RH-global specialisation and LH-local specialisation. Panel B presents Older Subgroup 2, who demonstrated an overall LVF/RH advantage. Panel C presents Older Subgroup 3, who demonstrated an overall RVF/LH advantage. Panel D presents Older Subgroup 4, who demonstrated reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation. In each panel, small dots represent data of each older participant across the four repeated-measures conditions: global targets in the LVF/RH, global targets in the RVF/LH, local targets in the LVF/RH, and local targets in the RVF/LH. Data from the same participant are connected with pale grey lines. Red lines represent participants who demonstrated faster RT in detecting global stimuli presented in the LVF/RH compared to RVF/LH (e.g., RH-global specialisation). Blue lines represent participants who demonstrated faster RT in detecting local stimuli presented in the RVF/LH compared to LVF/RH (e.g., LH-local specialisation).

4.3.3 Part 3. Age-Related Changes in Global-Local Processing at the Subgroup Level

A mixed-design ANOVA was conducted to examine whether the local-processing bias observed in the older age group was driven by the subgroup of older participants who did not demonstrate RH-global specialisation (i.e., the subgroup of older participants who demonstrated an overall RVF/LH advantage: $RT_{global\text{-}LVF} > RT_{global\text{-}RVF}$ and $RT_{local\text{-}LVF} > RT_{local\text{-}RVF}$). There was a significant main effect for Level ($F(1, 54) = 60.01$, $p < .001$, $\eta_p^2 = .53$, $BF_{10} > 10^{12}$), indicating that older participants were overall faster in detecting the local targets (M = 529.71 ms, 95% CI [501.25, 558.18]) compared to the global targets (M = 630.32 ms, 95% CI [607.44, 653.20]). The Bayes factors indicated that the data were more than 10^{12} times more likely to support H_1 compared to H_0 for the main effect of Level, providing strong evidence that older participants demonstrated differences in RT between global processing and local processing. There was no significant main effect for Older Subgroup ($F(3, 54) = 0.81$, $p = .50$, $\eta_p^2 = .04$, $BF_{01} = 4.73$) nor was there a significant Level × Older Subgroup interaction ($F(3, 54) = 0.48$, $p = .70$, $\eta_p^2 = .03$, $BF_{01} = 6.51$). The Bayes factor for the main effect of Older Subgroup indicated that the data were 4.73 times more likely to support H_0 compared to H_1, providing moderate evidence that there were no overall RT differences between the four older hemispheric asymmetry subgroups. The Bayes factor for the Level × Older Subgroup interaction indicated that the data were 6.53 times more likely to support H_0 compared to H_1, providing moderate evidence that there were no differences in RT for global processing compared to local processing across the four older hemispheric asymmetry subgroups. Overall, these findings demonstrate that for all four of the hemispheric asymmetry subgroups (i.e., both RH-global specialisation and LH-local specialisation, overall LVF/RH advantage, overall RVF/LH advantage, reversed hemispheric asymmetry—RH-local specialisation *and* LH-global specialisation), older participants consistently demonstrated a within-group local-processing bias (i.e., older participants were faster in detecting the local targets compared to the global targets). See Figure 4.4 for the estimated marginal means of the four hemispheric asymmetry subgroups in older participants.

Figure 4.4

Estimated Marginal Means for the Level × Older Subgroup Interaction in Older Participants



Note. Error bars represent Bonferroni-corrected 95% confidence intervals, and small dots represent the data for each participant.

4.4 Discussion

Hemispheric asymmetry has been widely documented for global-local processing, with the RH specialised for global processing and the LH specialised for local processing. However, individual differences in this hemispheric asymmetry have remained largely unexplored. The present study is the first systematic investigation of individual differences in hemispheric asymmetry for global-local processing in young and older adults.

In response to our first research question, the findings indicate that, regardless of visual field of presentation, older participants demonstrated a local-processing bias as well as an age-related worse performance for global processing when compared with young participants. In addition, our findings confirm that hemispheric asymmetry for global-local processing remains intact across the lifespan. Both young and older participant groups demonstrate RH-global specialisation and LH-local specialisation. In

response to our second research question, our findings reveal that there are substantial individual differences in hemispheric asymmetry for global-local processing within each age group. Not all participants demonstrated the expected hemispheric asymmetry pattern of RH-global specialisation and LH-local specialisation. In response to our third research question, our findings indicate that the age-related within-group local-processing bias was consistently observed across all subgroups of older participants, regardless of the different patterns of hemispheric asymmetry for global-local processing; that is, regardless of whether the participants demonstrated both RH-global specialisation and LH-local specialisation, or an overall RH/LVF advantage, or an overall LH/RVF advantage, or a reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation.

4.4.1 Implications for Group and Individual Differences in Hemispheric Asymmetry for Global-Local Processing

Our findings for group differences in hemispheric asymmetry (see Results, Part 1) indicate that both young and older participants demonstrated RH-global specialisation (i.e., faster performance for global targets presented in the LVF/RH compared to RVF/LH) and LH-local specialisation (i.e., faster performance for local targets presented in the RVF/LH compared to LVF/RH). These findings are consistent with previous studies reporting hemispheric asymmetry for global-local processing in young adults (Brederoo et al., 2019; Chen et al., 2024; Hübner, 1998; Oken et al., 1999; Peterson & Peterson, 2014; Sergent, 1982; Yovel et al., 2001) and in older adults (Chen et al., 2024; Oken et al., 1999), thus supporting the view that hemispheric asymmetry for global-local processing remains intact across the lifespan. Notably, the present study included a considerably larger sample size (127 young participants and 58 older participants) compared to previous studies that have reported hemispheric asymmetry for global-local processing (e.g., Brederoo et al., 2019: 21 young participants; Hübner, 1998: 8 young participants in Experiments 1 and 2; Oken et al., 1999: 20 young participants and 25 older participants; Peterson & Peterson, 2014: 48 young participants; Sergent, 1982: 12 young participants in Experiments 1 and 2; Yovel et al., 2001: 16 young participants in Experiment 1A and 59 young participants in Experiment 2). Despite the increase in statistical power in the

present study, the effects of hemispheric asymmetry for global-local processing remained relatively modest, with small to medium effect sizes for the differences between the LVF/RH and RVF/LH in both global processing and local processing across the two age groups.

Our findings for individual differences in hemispheric asymmetry (see Results, Part 2) indicate that, although the majority of participants demonstrated RH-global specialisation alongside LH-local specialisation, the expected pattern of hemispheric asymmetry was observed in only marginally more than 50% of the participants across the two age groups. Importantly, our findings identified distinctive subgroups when examining hemispheric asymmetry for global-local processing using a divided visual field design. Specifically, approximately one third of participants in the two subgroups (i.e., overall LVF/RH advantage, overall RVF/LH advantage) demonstrated an overall better performance in one visual field compared to the other visual field, and this better performance in one visual field was evident for both global processing and local processing. These findings warrant consideration, as there are three potential interpretations.

One interpretation is that these subgroups may demonstrate hemispheric involvement in global-local processing that does not match the expected patterns of RH-global specialisation and LH-local specialisation. Specifically, these subgroups may have greater involvement of one hemisphere compared to the other hemisphere when processing global and local information, leading to either an overall RH advantage or an overall LH advantage for global-local processing. Another interpretation is that these subgroups may have demonstrated different attentional allocation between the two visual fields because of the difficulty of the task design, which required attention across two different dimensions: (1) between the two visual fields, LVF and RVF; and (2) between the two processing levels, global level and local level. Consequently, participants experiencing task difficulty may have strategically prioritised attention to one visual field while compromising performance in the other visual field. To test which of the two interpretations is more plausible, future studies could consider following up these subgroups of participants using a focused-attention task, instead of a divided-attention

task. A focused-attention task would reduce task difficulty because attention is focused at only one processing level at a time (i.e., focused only on the global level *or* only on the local level). Findings of persistent overall better performance in the LVF/RH or in the RVF/LH, regardless of whether participants were focusing on the global level or the local level, would support the first interpretation that these subgroups demonstrate different hemispheric involvement in global-local processing. Conversely, findings of better performance in the LVF/RH as compared to the RVF/LH when focusing on the global level (i.e., RH-global specialisation) and better performance in the RVF/LH as compared to the LVF/RH when focusing on the local level (i.e., LH-local specialisation) would support the second interpretation of task-dependent attentional allocation.

The third interpretation is that the hemispheric asymmetry subgroups observed in the present study may partly reflect the measurement noise found with a behavioural divided visual field design. In this behavioural design, functional lateralisation is measured by comparing the difference in behavioural performance between the LVF and RVF. However, these behavioural measures may not always provide reliable or valid measures of hemispheric asymmetry. Most research on the reliability and validity of the behavioural divided visual field design has examined tasks measuring hemispheric specialisation for language processing. In these studies, it was reported that language lateralisation derived from the behavioural divided visual field design demonstrated low test-retest reliability (e.g., Parker et al., 2021; Parker et al., 2022; Voyer, 1998) and that there were inconsistent correlations between behavioural measures and neuroimaging measures of language lateralisation (e.g., Parker et al., 2022; Krach et al., 2006; also see Hunter & Brysbaert, 2008; Van der Haegen et al., 2011).

Notably, in the study by Van der Haegen et al. (2011), the researchers investigated atypical language lateralisation in 50 left-handed participants using two different naming tasks (i.e., a word naming task and a picture naming task) with a divided visual field design, which was followed by neuroimaging. The results indicated that behavioural and neuroimaging measures for language lateralisation were largely consistent for subgroups of participants who demonstrated clear-cut visual field performance. Specifically, left-handed participants who demonstrated a clear RVF advantage for both naming tasks

were more likely to demonstrate typical LH lateralisation for language processing in the neuroimaging data, and left-handed participants who demonstrated a clear LVF advantage for both naming tasks were more likely to demonstrate atypical RH lateralisation for language processing in the neuroimaging data. Importantly, the results were not as consistent for the subgroups of participants who demonstrated less clear-cut visual field performance or for those participants who demonstrated differences in visual field performance for the two different naming tasks. Overall, these findings indicated that, for some individuals, the divided visual field design may not provide a valid measure of their underlying hemispheric asymmetry.

To the best of our knowledge, no study has systematically investigated the reliability and validity of hemispheric asymmetry for global-local processing as measured in a behavioural divided visual field design. Future research is warranted to examine the test-retest reliability of the hemispheric asymmetry subgroups identified in the present study, to determine whether they reflect stable individual differences in hemispheric asymmetry for global-local processing. In addition, neuroimaging methods could also be incorporated to examine whether these hemispheric asymmetry subgroups of participants demonstrate lateralised neural activation patterns that are consistent with their behavioural performance.

Taken together, our findings for group and individual differences in hemispheric asymmetry have important methodological considerations for using the divided visual field design to examine hemispheric asymmetry for global-local processing. This hemispheric asymmetry emerges as a robust phenomenon when testing at the group level across young adults and older adults, with the majority of participants demonstrating both RH-global specialisation and LH-local specialisation. However, the effect sizes for this hemispheric asymmetry remain modest. This is potentially attributable to the systematic individual differences in task performance between the two visual fields, caused either by differences in hemispheric asymmetry or differences in attentional allocation during the task. These findings provide a potential explanation for previous studies that have failed to replicate hemispheric asymmetry for global-local processing when using relatively smaller sample sizes (Blanca & Alarcón, 2002: 19 young

participants in Experiment 1; Boles, 1984: 16 young participants in Experiments 1 and 2; Boles & Karner, 1996: 18 young participants; Van Kleeck, 1989: 24 young participants), underscoring the need for future studies to justify their sample sizes.

4.4.2 Implications for Age-Related Changes in Global-Local Processing

Our findings for group differences in global-local processing (see Results, Part 1) indicate that older adults demonstrate an age-related worse performance for global processing compared to young adults, whereas local processing remains intact with age. Previous studies (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002) have reported that global-local processing is influenced by healthy ageing, with older adults demonstrating a local-processing bias. However, these findings were based on within-group comparisons, demonstrating a better performance for global processing compared to local processing in the older adult group. Chen et al. (2024) directly compared the findings for young and older adults and demonstrated that the age-related local-processing bias reported in previous studies was better explained by worse performance for global processing for older adults. The between-group comparisons (between the young and older adult groups) established that local processing is an important baseline—healthy ageing does not influence performance for local processing, but global processing is worse in older adults compared to young adults. These findings have potential diagnostic value; for example, for differentiating typical from atypical cognitive ageing by including a global-local processing task in clinical testing (see Álvarez-San Millán et al., 2022).

In addition to the findings of age-related worse performance for global processing, our group findings for hemispheric asymmetry (see Results, Part 1) confirm that older adults demonstrate RH-global specialisation and LH-local specialisation, similar to that of young adults. These hemispheric asymmetry findings were consistent with Chen et al. (2024) and Oken et al. (1999), who reported that RH specialisation for global processing remains intact with healthy ageing.

Altogether, our group findings do not support the right-hemisphere ageing hypothesis. Although older participants did demonstrate an age-related worse

performance in global processing, the RH of older participants was still more efficient compared to the LH at processing global information. The right-hemisphere ageing hypothesis was further examined in the present study by categorising older participants into four hemispheric asymmetry subgroups: (1) both RH-global specialisation and LH-local specialisation; (2) overall RH/LVF advantage (i.e., faster in the LVF regardless of the global-local processing level); (3) overall LH/RVF advantage (i.e., faster in the RVF regardless of the global-local processing level); (4) reversed hemispheric asymmetry—RH-local specialisation and LH-global specialisation. The subgroup findings (see Results, Part 3) revealed that the within-group local-processing bias was consistently observed across all four hemispheric asymmetry subgroups of older participants. These findings at the subgroup level once again do not support the right-hemisphere ageing hypothesis. The age-related worse performance for global processing in older adults occurs regardless of whether the RH was more efficient compared to the LH in global processing and/or whether the LH was more efficient compared to the RH in local processing. Future research is warranted to investigate the mechanisms underlying these age-related changes in global processing.

The right-hemisphere ageing hypothesis has been examined with two types of behavioural studies using a divided visual field design. The first type of behavioural study concerns spatial attention to the LVF compared to the RVF, regardless of the type of information being processed in that visual field. Specifically, these studies compared the overall attention of young and older adults to information presented in the LVF (initially processed by the RH) *versus* the RVF (initially processed by the LH). Supporting evidence for the right-hemisphere ageing hypothesis in this type of behavioural study includes research by Schmitz and Peigneux (2011) and by Guilbert et al. (2019). Schmitz and Peigneux (2011) used a perceptual landmark task and reported that, compared to young adults, older adults demonstrated a rightward attentional bias in this task with the right half of lines perceived as being longer than the left half of lines. Guilbert et al. (2019) used Posner's (1980) spatial cueing paradigm and reported that older adults demonstrated greater difficulty disengaging attention from a cue appearing in the RVF and reorienting attention to a target appearing in the LVF, as compared to disengaging attention from a cue appearing in the LVF and reorienting attention to a target appearing in the RVF. The

implication of the findings from Schmitz and Peigneux was that, compared to young adults, older adults demonstrate an attentional bias towards the RVF whereas, the implication from the findings of Guilbert et al. was that age-related attentional biases may relate to greater difficulties in disengaging attention from the RVF and reorienting attention to the LVF. In contrast to the support for the right-hemisphere ageing hypothesis in this first type of behavioural study, our group-level findings did not provide support for the right-hemisphere ageing hypothesis. The older adults in our study did not demonstrate overall better performance in the LVF/RH when compared to the RVF/LH. Instead, the performance of our older adults for stimuli presented in the LVF/RH was comparable to their performance in the RVF/LH, regardless of whether the stimuli were global stimuli or local stimuli.

The second type of behavioural study used the divided visual field design to examine age-related changes in functional hemispheric asymmetry for specific cognitive domains. Supporting evidence for the right-hemisphere ageing hypothesis in the domain of face processing comes from Prodan et al. (2007), who reported reduced RH specialisation for face processing in older adults compared to young adults. But many of the studies using the divided visual field design have not provided consistent support for the right-hemisphere ageing hypothesis. For example, Beaton et al. (2012) and Hausmann et al. (2003) reported that RH specialisation for face processing remained intact with age. To the best of our knowledge, there are only three studies (Chen et al., 2024; Oken et al., 1999; the present study) that represent this second type of behavioural study in the domain of global-local processing, and none of these studies have found support for the right-hemisphere ageing hypothesis. Instead, these studies have reported that RH specialisation for global processing remained intact with age.

In addition to the right-hemisphere ageing hypothesis, *the model 'hemispheric asymmetry reduction in older adults'* (HAROLD) provides another account of age-related changes in functional hemispheric asymmetry. The HAROLD model proposes that older adults tend to recruit both hemispheres to process tasks that are typically processed by only one hemisphere in young adults (Cabeza, 2002). This model has received support from neuroimaging evidence on age-related changes across a range of prefrontal

cognitive functions, including episodic memory (e.g., Bäckman et al., 1997; Cabeza et al., 1997), semantic memory (e.g., Stebbins et al., 2002), working memory (e.g., Reuter-Lorenz et al., 2000), and inhibitory control (e.g., Nielson et al., 2002). Our group-level findings comparing young participants and older participants did not provide support for the HAROLD model. This model would predict that, in older adults, global information would be processed by both hemispheres rather than predominantly by the RH, and local information would be processed by both hemispheres rather than predominantly by the LH. In contrast, our findings suggested that in older adults, the RH is still more efficient than the LH for processing global information, and that the LH is still more efficient than the RH for processing local information. Future studies are warranted to provide converging neuroimaging evidence for the behavioural findings of hemispheric asymmetry for global-local processing in the present study for young adults and older adults.

4.4.3 Limitations and Future Directions

While the present findings open new research avenues for investigating individual differences in hemispheric asymmetry for global-local processing, there were several limitations. The first limitation concerns sample size. Although the sample size of the present study is considered large for behavioural studies investigating hemispheric asymmetry for global-local processing at the group level, it may still be insufficient for individual-level analyses. In particular, chi-square tests typically require substantially larger sample sizes compared to those typically collected in the area of global-local processing research. As the first behavioural study to investigate individual differences in hemispheric asymmetry—categorising participants into hemispheric asymmetry subgroups—we reported the minimal detectable effects for these individual-level analyses based on the actual sample sizes. In addition, we reported Bayes factors for the individual-level findings. Future studies with larger and more balanced samples across the two age groups and the four hemispheric asymmetry subgroups are needed to replicate the individual-level findings reported here.

The second limitation concerns the handedness assessment. Although all our young and older participants were screened with the Edinburgh Handedness Inventory, we did not ask participants about their history of right-handedness. Given that in the past it was a common practice to force left handers to write with their right hand, future research on age-related changes in hemispheric asymmetry could include such a question to account for corrections in handedness during childhood.

4.5 Conclusion

Hemispheric asymmetry has been documented for global-local processing, with the RH more efficient for global processing and the LH more efficient for local processing. In the present study, there are three key new findings regarding hemispheric asymmetry for global-local processing. First, hemispheric asymmetry for global-local processing is stable across the lifespan, with both young and older adults demonstrating more efficient global processing in the LVF/RH and more efficient local processing in the RVF/LH. However, the effect size of this hemispheric asymmetry as observed in a behavioural paradigm remains modest despite a relatively large sample size being adopted in the present study (127 young participants and 58 older participants). Our findings may explain why previous studies have failed to replicate hemispheric asymmetry for global-local processing when using relatively smaller sample sizes, and indicate there is a need for careful consideration of sample size in future behavioural studies. Second, while RH-global specialisation and LH-local specialisation remains a robust finding when analysing participants' group-level findings, substantial individual differences exist, both for young and older adults. Further research is warranted to clarify whether these individual differences reflect variations in hemispheric involvement within individuals or whether they are driven by the task demands of a divided-attention behavioural paradigm that requires concurrent allocation of attention both to the left and right visual field and to the global and local processing level. Third, healthy ageing influences global processing, whereas local processing remains intact in older adults. Importantly, this age-related decline in global processing occurs independently of whether older adults demonstrate the predicted overall RH-global specialisation or LH-local specialisation. In other words, the age-related decline in global processing observed at the group level is

not caused by an older subgroup who do not demonstrate RH-global specialisation. Together, our findings underscore the importance of investigating both group and individual differences to understand the mechanism of hemispheric asymmetry for global-local processing, and to understand how this relates to visual attention across the life span.

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Chapter 5 Global-Local Processing and the Ebbinghaus Illusion: Group and Individual Differences in Young and Older Adults

Publication Note

The study presented in this chapter has been published as:

Chen, H. & Aimola Davies, A. M. (2025). Global-local processing and the Ebbinghaus Illusion: Group and individual differences in young and older adults. Perception, 55(4), 384–411. https://doi.org/10.1177/03010066251395949

Abstract

The Ebbinghaus illusion is a size illusion, in which a central circle appears larger or smaller depending on the size of surrounding circles. This illusion is widely used to study group-level differences in attentional processing, with the proposal that a local-processing bias reduces susceptibility to the Ebbinghaus illusion. One-hundred and forty-five participants (87 young; 58 older) were included in the analyses. Participants completed the Navon hierarchical-figures task to measure the global-local processing bias, and the Ebbinghaus illusion task, to measure susceptibility to the illusion. First, we investigated whether a strong local-processing bias reduced susceptibility to the Ebbinghaus illusion. Our findings did not support this proposal. At the group level, older participants demonstrated worse performance for global processing compared to young participants, but there were no age-group differences in susceptibility to the illusion. At the individual level, the young and older participants with the stronger local-processing bias were the participants with greater susceptibility to the illusion. Second, we investigated whether longer inspection times during the Ebbinghaus illusion task reduced susceptibility to the illusion. Our findings did support this proposal. At the group level,

there were no age-group differences in either inspection time to the Ebbinghaus illusion or susceptibility to the illusion. At the individual level, we replicated previous findings—the participants with the longer inspection times were the participants with the least susceptibility to the illusion. We discuss alternative cognitive mechanisms that may account for the Ebbinghaus illusion and their relevance to age-related changes and individual differences in visual attention.

5.1 Introduction

Our perception of reality is derived from what we see, but what we perceive does not always accurately represent the physical reality of the external environment. Visual illusions are one of these examples where perception diverges from physical reality (Gregory, 2009). Perception of visual illusions can occur at various stages of processing (Coren & Girgus, 1978); for example, at the sensory processing stage, where light input is distorted by optical structures or optical-neural interactions, or at the cognitive processing stage, where interpretation of incoming information can be influenced by visual attentional mechanisms and cognitive strategies. Visual illusions can serve as powerful tools for understanding the visual system.

The Ebbinghaus illusion (also known as the Titchener illusion) is a classic visual illusion that distorts size perception. In this illusion, a central circle is perceived to be larger compared to its physical size when surrounded by smaller contextual circles, or smaller compared to its physical size when surrounded by larger contextual circles (Ebbinghaus, 1902; Titchener, 1901). The Ebbinghaus illusion is proposed to be influenced by visual attentional mechanisms, such as global-local processing (e.g., Happé, 1996). Global-local processing involves directing attention globally (i.e., to the overall visual scene) or locally (i.e., to the finer details within the visual scene). Individual differences in preference for global processing *versus* local processing have been observed, leading to the identification of two processing styles: (1) a global-processing bias, in which individuals attend globally; (2) a local-processing bias, in which individuals attend locally (see Happé, 1999; Happé & Frith, 2006).

Happé (1996) was the first to propose that a local-processing bias may reduce susceptibility to the Ebbinghaus illusion. In this study, children on the autistic spectrum—who are believed to show a local-processing bias due to weakened central coherence (Shah & Frith, 1983; Shah & Frith, 1993)—were reported to demonstrate reduced susceptibility to the Ebbinghaus illusion compared to neurotypically developing children. These findings of reduced susceptibility to the Ebbinghaus illusion led to the development of the visual attentional integration theory. According to this theory, in neurotypical individuals, the Ebbinghaus illusion arises when the central circle and the contextual circles are integrated and processed as a global configuration. Individuals with a local-processing bias will have reduced susceptibility to the Ebbinghaus illusion because of a weakening in the strength of this visual attentional integration, leading to the processing of the central circle separately from the contextual circles.

5.1.1 Ebbinghaus Illusion as a Measure of Group-Level Differences in the Global-Local Processing Bias

The Ebbinghaus illusion has been used extensively to measure group-level differences in global-local processing, with differences in susceptibility to the Ebbinghaus illusion interpreted as differences in a bias for either global processing or local processing. One of the earliest of these studies was conducted by Phillips et al. (2004), who developed a computerised paradigm for the Ebbinghaus illusion and used this paradigm to measure sex differences in the global-local processing bias. In their classic Ebbinghaus illusion setup, stimuli were positioned side-by-side, with one central circle surrounded by smaller contextual circles, and the other central circle surrounded by larger contextual circles (see Methods, Figure 5.1A). A forced-choice response was used, in which participants were asked to decide whether the larger central circle was on the left or on the right of the presentation. Phillips et al. reported that male participants were more accurate at this task compared to female participants. These results were interpreted to mean that males demonstrated a stronger local-processing bias compared to females, consequently resulting in their reduced susceptibility to the Ebbinghaus illusion. Phillips et al. suggested that their findings regarding sex differences in susceptibility to the Ebbinghaus illusion were in line with previous studies (e.g., Baron-

Cohen et al., 2003; see Voyer et al., 1995 for a systematic review) that had used different experiment paradigms to indicate a local-processing bias in males compared to females. Phillips et al. concluded that the Ebbinghaus illusion paradigm can serve as a specific and sensitive measure to investigate group-level differences in the global-local processing bias.

Following the study by Phillips et al. (2004), numerous studies have investigated Happé's (1996) visual attentional integration theory by using the Ebbinghaus illusion to measure group-level differences in the global-local processing bias across cultural, political, and clinical contexts. Group-level differences in the global-local processing bias have been demonstrated between: Eastern and Western cultures (e.g., Doherty et al., 2008; Imada et al., 2013; Köster et al., 2018; Mok & Morris, 2012; Schulze et al., 2022); remote and urban cultures (e.g., Caparos et al., 2012; Caparos & Boissin, 2024; Davidoff et al., 2008; de Fockert et al., 2007; Mavridis et al., 2020); left-oriented and right-oriented political groups (e.g., Caparos et al., 2015); gamers and non-gamers (e.g., Kütük et al., 2022); clinical and non-clinical groups (e.g., Horton & Silverstein, 2011; Joseph et al., 2013; Mittal et al., 2015; Silverstein et al., 2013).

The Ebbinghaus illusion has been used extensively to investigate the global-local processing bias, including in studies of the developmental trajectory of the bias in children (e.g., Doherty et al., 2010). What remains relatively underexplored is the investigation of group-level differences of the bias in young adults and older adults. To the best of our knowledge, only five studies (Coren & Porac, 1978; Eisner & Schaie, 1971; Grzeczkowski et al., 2017; Mazuz et al., 2024; Wapner et al., 1960; see Table 5.1 for methodological differences in these studies) have examined the Ebbinghaus illusion in older adults. Of these studies, only Wapner et al. and Mazuz et al. directly compared age-group differences (between young adults and older adults) in susceptibility to the Ebbinghaus illusion. And, both Wapner et al. and Mazuz et al. reported reduced susceptibility to the Ebbinghaus illusion in older adults compared to young adults. Although these studies did not interpret their findings in terms of group-level differences in the global-local processing bias, the finding of an age-related difference in susceptibility to the Ebbinghaus illusion is in line with studies using various other

experiment paradigms to demonstrate that older adults have a local-processing bias (see Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002; also see Chen et al., 2024).

Table 5.1

Methodological Differences in Studies of the Ebbinghaus Illusion with Young and Older Adults

Study [a]	Participants *N* / Age: Young	Participants *N* / Age: Older	Participant inclusion criteria (Before screening for outliers)	Stimulus presentation	Response task	Inclusion of inspection time	Stimulus presentation duration	ITI/fixation	*N* of trials	Dependent variable(s)
1 Wapner et al. (1960)	*N* = 20 / 20–29 years	*N* = 20 / 65–80 years	X	Two experiment trial stimuli side-by-side, each arranged in a circular configuration.	Judged whether central circle on right was larger, equal, or smaller than central circle on left.	X	NR	NR	34	Point of subjective equality.
2 Eisner & Schaie (1971)	*N* = 135 / 55–75 years		X	Two experiment trial stimuli side-by-side, each arranged in a circular configuration.	Judged whether central circle on right was larger, equal, or smaller than central circle on left.	X	NR	NR	34	Point of subjective equality.
3 Coren & Porac (1978)	*N* = 688 / 5–75 years		X	One experiment trial stimulus, arranged in a circular configuration: 'overestimated' condition (with smaller contextual circles) or 'underestimated' condition (with larger contextual circles).	Judged size of central circle, by selecting circle which appeared to be equal in size from graded series of circles.	X	NR	NR	NR	Size difference between central circle and circle selected.
4 Grzeczkowski et al. (2017)	*N* = 144 / 6–81 years (*Md* = 22)		X	Two experiment trial stimuli side-by-side, each arranged in a circular configuration.	Adjusted size of adjustable central circle on right to size of reference central circle on left.	X	No time restriction	NA	2	Size difference between reference central circle and circle adjusted.
5 Mazuz et al. (2024)	*N* = 80 / 20–39 years	*N* = 80 / 61–85 years	X	Two experiment trial stimuli side-by-side, each arranged in a circular configuration.	Decided which of two central circles looked larger.	√	1000 ms	1000 ms fixation	141	Constant error; Just noticeable difference.
6 Present Study (2025)	*N* = 87 / 18–30 years (*M* = 21.49)	*N* = 58 / 57–88 years (*M* = 71.72)	• Normal/corrected-to-normal vision. • No history of self-reported neurological impairments. • MoCA: No evidence of cognitive impairment for older participants • 80% accuracy on catch trials.	Two experiment trial stimuli or two catch trial stimuli side-by-side, each arranged in a square configuration.	Decided which of two central circles looked larger.	√	Until response: maximum 5000 ms	200ms ITI	96 (80 experiment trials, 16 catch trials)	Point of subjective equality.

Note. The studies are listed in chronological order (publication year). NR = not reported; NA = not applicable; *Md* = median; *M* = mean; MoCA = Montreal Cognitive Assessment; ITI = inter-trial interval.

[a] In Studies 1, 5, and 6, group-level differences in young and older adults' susceptibility to the Ebbinghaus illusion were investigated.

In Studies 2, 3, and 4, older adults were included as participants, but their performance was not directly compared to the performance of young participants.

5.1.2 Ebbinghaus Illusion as a Measure of Individual-Level Differences in Global-Local Processing

While Happé's (1999) visual attentional integration theory has been widely applied for measuring group-level differences in the global-local processing bias, a critical gap exists in the literature concerning whether this theory can account for individual-level differences in the bias. What remains largely unexplored is whether measuring the global-local processing bias using an experiment paradigm other than the Ebbinghaus illusion (e.g., a hierarchical-figures paradigm) will also provide support for the finding that individuals with the stronger local-processing bias (as compared with individuals with a stronger global-processing bias) are less susceptible to the Ebbinghaus illusion. Navon's (1977) hierarchical-figures paradigm is another widely used experiment paradigm for measuring the global-local processing bias. In this paradigm, a hierarchical figure comprises a large stimulus (i.e., the global-level stimulus) constructed from smaller stimuli (i.e., the local-level stimuli) (see Figure 5.1B for examples). To the best of our knowledge, only two studies (Caparos et al., 2012; Caparos et al., 2015) have employed the hierarchical-figures paradigm and the Ebbinghaus illusion paradigm together to examine group-level differences in the global-local processing bias, and only Caparos et al. (2012) extended this investigation to include statistical analyses of individual-level differences.

Caparos et al. (2012) examined the global-local processing bias[1] across four cultural groups: Japanese, British, traditional Himba (i.e., semi-nomadic Namibians), and urbanised Himba. For the hierarchical-figures paradigm, the group-level findings revealed that traditional Himba participants demonstrated the strongest local-processing bias (followed by urbanised Himba and British participants), and that Japanese participants demonstrated the strongest global-processing bias. For the

[1] Caparos et al. (2012) adopted a similarity-matching task, in which three hierarchical figures were presented: one target hierarchical figure and two test hierarchical figures. The test hierarchical figures were made up either of the same global-level stimuli as the target hierarchical figure (i.e., a global-matching test), or the same local-level stimuli as the target hierarchical figure (i.e., a local-matching test). Participants were asked to identify which of the two test hierarchical figures appeared most like the target hierarchical figure.

Ebbinghaus illusion paradigm, the group-level findings revealed that traditional Himba participants were least susceptible to the Ebbinghaus illusion (followed by urbanised Himba and British participants), and that Japanese participants were most susceptible to the Ebbinghaus illusion. These group-level findings were consistent with Happé's (1996) visual attentional integration theory—the participant groups with a local-processing bias (e.g., traditional Himba participants) were less susceptible to the Ebbinghaus illusion, and the participant groups with a global-processing bias (e.g., Japanese participants) were more susceptible to the Ebbinghaus illusion. Importantly, the individual-level correlations revealed that performance on the hierarchical-figures paradigm was not significantly correlated with that of the Ebbinghaus illusion paradigm, which suggests that the individuals with the stronger local-processing bias were not necessarily the individuals who were less susceptible to the Ebbinghaus illusion.

These individual-level findings reported by Caparos et al. (2012) have been used to challenge the validity of Happé's (1996) visual attentional integration theory. While Happé's original research focused on group-level differences, some researchers (e.g., Bressan & Kramer, 2021) have suggested that the theory should be capable of being extended to individual-level differences. Bressan and Kramer argued that the inconsistencies between the group-level and individual-level findings in the Caparos et al. study indicate that the previously reported group-level differences in susceptibility to the Ebbinghaus illusion may have been driven by factors other than the global-local processing bias. One such factor is response effort. Participants may expend greater effort when making size judgements, taking a longer time to inspect the Ebbinghaus illusion. In their study, Bressan and Kramer found that the individuals who spent a longer time inspecting the Ebbinghaus illusion were the individuals who were less susceptible to the Ebbinghaus illusion. They pointed out that inspection time has not been controlled for or even considered to be important in most previous studies that have used the Ebbinghaus illusion paradigm to examine group-level differences in the global-local processing bias, including in the study by Caparos et al. (2012). They conjectured that the traditional Himba participants may have spent a longer time inspecting the Ebbinghaus

illusion compared to the other groups of participants, resulting in the observed reduction in susceptibility to the Ebbinghaus illusion among traditional Himba participants.[2]

5.1.3 Present Study

In the present study, we used Phillips et al.'s (2004) Ebbinghaus illusion paradigm to measure susceptibility to the Ebbinghaus illusion, and Navon's (1977) hierarchical-figures paradigm to measure the global-local processing bias. For the hierarchical-figures paradigm, we used a divided-attention task in which participants were instructed to attend simultaneously to the global level and to the local level of the hierarchical figure, and to respond to a target. The target could appear either at the global level or at the local level. This setup allowed participants to allocate greater attention to their preferred processing level, thus reflecting their predisposed global-local processing bias.

Our first research question concerned the relationship between the global-local processing bias (as measured by the hierarchical-figures paradigm) and susceptibility to the Ebbinghaus illusion at the group level, between young participants and older participants. Previous studies using the hierarchical-figures paradigm (see Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002; also see Chen et al., 2024) have reported that older adults demonstrate a local-processing bias compared to young adults. Our aim was to replicate these findings of an age-related local-processing bias, and to investigate whether this local-processing bias on the hierarchical-figures paradigm was associated with reduced susceptibility to the Ebbinghaus illusion in older participants compared to young participants.

Our second research question concerned the relationship between the global-local processing bias (as measured by the hierarchical-figures paradigm) and susceptibility to the Ebbinghaus illusion at the individual level for young participants and older participants. Our aim was to investigate whether the individuals with a stronger local-

[2] Specifically, Bressan and Kramer (2021) argued that, in the study by Caparos et al. (2012), the finding of reduced susceptibility to the Ebbinghaus illusion may be better explained by the traditional Himba participants being more engaged with the task, either due to their unfamiliarity with the modern geometric shapes used in the study (i.e., the arrays of circles used in the Ebbinghaus illusion task) or because their participation in the experiment was in exchange for daily necessities.

processing bias on the hierarchical-figures paradigm would be the individuals with less susceptibility to the Ebbinghaus illusion.

Our third research question concerned the relationship between susceptibility to the Ebbinghaus illusion and inspection time of the illusion at both the group and individual level for young participants and older participants. Building on the study of Bressan and Kramer (2021), we investigated whether a longer inspection time of the Ebbinghaus illusion would be associated with reduced susceptibility to the Ebbinghaus illusion.

5.2 Methods

5.2.1 Participants

A total of 158 participants were recruited for this study, and 145 participants (87 young participants, 58 older participants) were included in the final statistical analyses. All participants self-reported being of 100% European ancestry. Young participants were students from the Australian National University and students from the University of Oxford. Older participants were recruited from the University of the Third Age and the broader community in Canberra. Participants were excluded from statistical analyses if they did not meet the following five inclusion criteria:

1. Normal or corrected-to-normal vision, as indicated by in-laboratory testing with a Snellen chart (Snellen, 1868).
2. No history of self-reported neurological impairments.
3. No evidence of cognitive impairment as assessed by the Montreal Cognitive Assessment (MoCA; Nasreddine, 1996), with a score of 24 or greater indicating intact cognitive functioning (see Pugh et al., 2018; Thomann et al., 2020). Including older adults with mild cognitive impairment in the study may have increased the likelihood of observing reduced susceptibility to the Ebbinghaus illusion in the older participant group, as indicated by some researchers (e.g., Álvarez-San Millán et al., 2022) who found that older adults with mild cognitive impairment

demonstrated a stronger local-processing bias compared to cognitively healthy older adults.[3]

4. Overall accuracy of 80% or greater on the *target-absent trials* for the hierarchical-figures task. No response was required on these trials, as no target was presented (see 5.2.2 Apparatus, Stimuli, and Procedure). A response to a target-absent trial could have indicated that the participant either did not discriminate targets from distractors or responded quickly but with low accuracy.
5. Overall accuracy of 80% or greater on the catch trials for the Ebbinghaus illusion task. The stimulus design of the catch trials accentuated the perceptual size difference between the two central circles, so that the physically larger central circle was perceived as notably larger than the physically smaller central circle (see Figure 5.1A). An incorrect response to a catch trial indicated that the participant either did not understand the task instructions or did not comply with the instruction to choose the visually larger central circle.
6. The point of subjective equality score for the Ebbinghaus illusion task (computed to measure susceptibility to the Ebbinghaus illusion, see Statistical Analysis Plan) did not exceed three standard deviations away from the mean for each of the two age groups.[4]

No exclusions were required for criteria 1, 2, or 3. Two older participants were excluded for criterion 4, six young participants and three older participants were excluded for criterion 5, and one young participant and one older participant were excluded for criterion 6. See Table 5.2 for the young and older participants' demographic information. Power analyses using G*Power (version 3.1) indicated that a minimum of 63

[3] In the two studies (Wapner et al., 1960; Mazuz et al., 2024) reporting age group differences in susceptibility to the Ebbinghaus illusion between young and older adults, there was no screen for mild cognitive impairment in the older adult group (criterion 3). See Table 5.1 for methodological differences.

[4] This inclusion criterion was also expected to screen out participants who adopted a response strategy of always selecting the central circle surrounded by smaller or larger contextual circles. Such a response strategy would likely produce consistently low accuracy across the five size difference conditions, rather than an increase in accuracy as the physical size difference between the two central circles increased. This response strategy would likely result in an unusually extreme PSE score.

young participants and 43 older participants was required to detect a significant group-level difference in an independent samples *t* test (*d* = 0.50; power = 80%; α = .05; sample size ratio = 1.50). All participants provided written consent prior to participation in the study and received monetary compensation (or course credit for eligible young participants). The study was approved by the Human Research Ethics Committee at the Australian National University (Protocol: 2013/605 and 2019/795) and the University of Oxford (Protocol: 2010/87). A subset of the participants in the present study was previously reported in Chen et al. (2024).

Table 5.2

Demographic Information for Young and Older Participants Included in the Statistical Analyses

Demographic information	Young participants	Older participants
N	87	58
Female (*n*, %)	47, 54.02%	38, 65.52%
Male (*n*, %)	40, 45.98%	20, 34.48%
Age		
Mean	21.49	71.72
SD	3.01	7.32
Range	18–30	57–88
Highest level of education (*n*, %)		
Secondary	-	4, 6.90%
College	62, 71.26%	7, 12.07%
Undergraduate	11, 12.64%	29, 50.00%
Masters	10, 11.49%	7, 12.07%
Doctoral	4, 4.60%	7, 12.07%
Other	-	4, 6.90%
Experimenter (*n*, %) [a]		
1	47, 54.02%	-
2	16, 18.39%	25, 43.10%
3	24, 27.59%	33, 56.90%

Note. [a] Data collection was conducted across two locations by three experimenters. Experimenter 1 recruited young participants studying at the University of Oxford. Experimenters 2 and 3 recruited young participants studying at the Australian National University and older participants from the local Canberra community.

5.2.2 Apparatus, Stimuli, and Procedure

Participants were tested individually in a distraction-free room. The hierarchical-figures task was conducted first, followed by the Ebbinghaus illusion task. Both tasks were presented on a desktop monitor. A forehead-and-chin rest was used to maintain a constant eye-to-screen viewing distance for each participant. Reaction times (RT) and accuracy were recorded using a response pad for the hierarchical-figures task and a computer keyboard for the Ebbinghaus illusion task. See Table 5.3 for apparatus details.

5.2.2.1 Hierarchical-Figures Task. The hierarchical figures—large letters (size = 2.30° × 3.08°–3.90°) composed of seven to 14 small local letters (size = 0.40° × 0.50°)—were presented in black against a white background. There were two types of letters: targets (i.e., H, S, T) and distractors (i.e., D, C, E, K, L, U, V). See Table 5.3 for the full details of the letter stimuli. Within each hierarchical figure, a target was either presented (target-present hierarchical figure) or not presented (target-absent hierarchical figure). There were two types of target-present hierarchical figures: global-target figures (one target appeared at the global level and one distractor appeared at the local level) and local-target figures (one target appeared at the local level and one distractor appeared at the global level). The target-absent figures were made up of two different distractors (one distractor appeared at the global level and one distractor appeared at the local level). See Figure 5.1B for examples of the hierarchical figures, including global-target figures, local-target figures, and target-absent figures.

Participants were familiarised with the hierarchical figures to be used in the task before completing two practice blocks. Feedback about accuracy was provided in the practice blocks to ensure participants' understanding and compliance with the task instructions. In the experiment block, each trial began with a central fixation cross, followed by a hierarchical figure presented unilaterally either to the left visual field (LVF) or to the right visual field (RVF), and then two post-stimulus masks were presented bilaterally. All trials were presented in a randomised order, with the hierarchical figure randomly presented either to the LVF or to the RVF in equal proportions. The medial edges of the hierarchical figures were positioned 0.50° to the left or to the right of the central fixation cross. Participants were instructed to focus on the central fixation cross and to

respond to the targets as quickly and as accurately as possible, by pressing a button on the response pad (with their right index finger) when they saw a target appear at either the global level or the local level. Participants were also instructed not to respond if a target did not appear at either the global level or the local level. Feedback about accuracy was not provided in the experiment block. See Table 5.3 for details of the hierarchical-figures task design.

Table 5.3

Apparatus and Experiment Design for the Hierarchical-Figures Task

Apparatus and experiment design	Experimenter 1	Experimenter 2	Experimenter 3
Apparatus			
Display size	17 inches	18 inches	27 inches
Resolution	1024 × 768	1280 × 1024	2560 × 1440
Frequency	75 Hz	85.26 Hz	60 Hz
Viewing distance	50 cm	50 cm	57 cm
Hierarchical-figures task			
Programming software	E-Prime 2.0	E-Prime 2.0	Inquisit 6.2.1
Response pad	Chronos PST-100430	Chronos PST-100430	Cedrus RB-844
Stimuli			
Targets	H, T	S, T	S, T
Distractors	D, E, U, V	D, C, K, L, U, V	D, C, K, L, U, V
Global-target stimulus [a]	H-E, H-D, T-V, T-U	S-K, S-V, T-C, T-U	S-K, S-V, T-C, T-U
Local-target stimulus	V-H, U-H, E-T, D-T	K-S, V-S, C-T, U-T	K-S, V-S, C-T, U-T
Target-absent stimulus	D-E, D-V, E-V, E-U, U-D, U-V, V-E, V-D	D-K, D-V, K-D, V-D, L-C, L-U, U-L, C-L	D-K, D-V, K-D, V-D, L-C, L-U, U-L, C-L
Presentation duration			
Fixation cross	1000 ms	500 ms	500 ms
Hierarchical figure	150 ms	150 ms	150 ms
Post-stimulus mask	1500 ms	1000 ms	1000 ms
Inter-trial interval	-	1000 ms	1000 ms
N of trials			
Global-target figure	64	48	32
Local-target figure	64	48	32
Target-absent figure	128	96	64

Note. [a] Each pairing indicates the stimuli for one hierarchical figure, where the first letter indicates the global stimulus and the second letter indicates the local stimulus (e.g., H-E = a global 'H' stimulus made up of local 'E' stimuli).

5.2.2.2 The Ebbinghaus Illusion Task. The Ebbinghaus illusion task used in the present study was developed by Phillips et al. (2004). The Ebbinghaus illusion task comprised 96 trials, including 80 experiment trials and 16 catch trials. The stimuli consisted of two separate 3 × 3 arrays of nine solid black circles against a white background. The stimuli in each experiment trial featured two central circles, each of which was surrounded by eight contextual circles. One of the two central circles had a fixed diameter of 100 pixels (one pixel subtended 0.034° for Experimenter 1, 0.028° for Experimenter 2, and 0.023° for Experimenter 3), while the other central circle was either larger in size (with five possible larger diameters = 102, 106, 110, 114, 118 pixels) or smaller in size (with five possible smaller diameters = 82, 86, 90, 94, 98 pixels). An additional feature of the experiment trial stimuli was that the larger of the two central circles was surrounded by larger contextual circles (diameter = 125 pixels), and the smaller of the two central circles was surrounded by smaller contextual circles (diameter = 50 pixels). These features of the experimental trial stimuli yielded ten possible percentage size differences between the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles (i.e., $\left(\frac{\text{Size of central circle with larger contextual circles}}{\text{Size of central circle with smaller contextual circles}}\right) \times 100\%$): 102.00% (102 pixels/100 pixels), 102.04% (100 pixels/98 pixels), 106.00% (106 pixels/100 pixels), 106.38% (100 pixels/94 pixels), 110.00% (110 pixels/100 pixels), 111.11% (100 pixels/90 pixels), 114.00% (114 pixels/100 pixels), 116.28% (100 pixels/86 pixels), 118.00% (118 pixels/100 pixels), and 121.95% (100 pixels/82 pixels). This configuration of the experiment trial stimuli reduced the perceived size difference between the two central circles. Specifically, the larger of the two central circles appeared smaller than its physical size because it was surrounded by contextual circles larger than itself, whereas the smaller of the two central circles appeared larger than its physical size because it was surrounded by contextual circles smaller than itself.

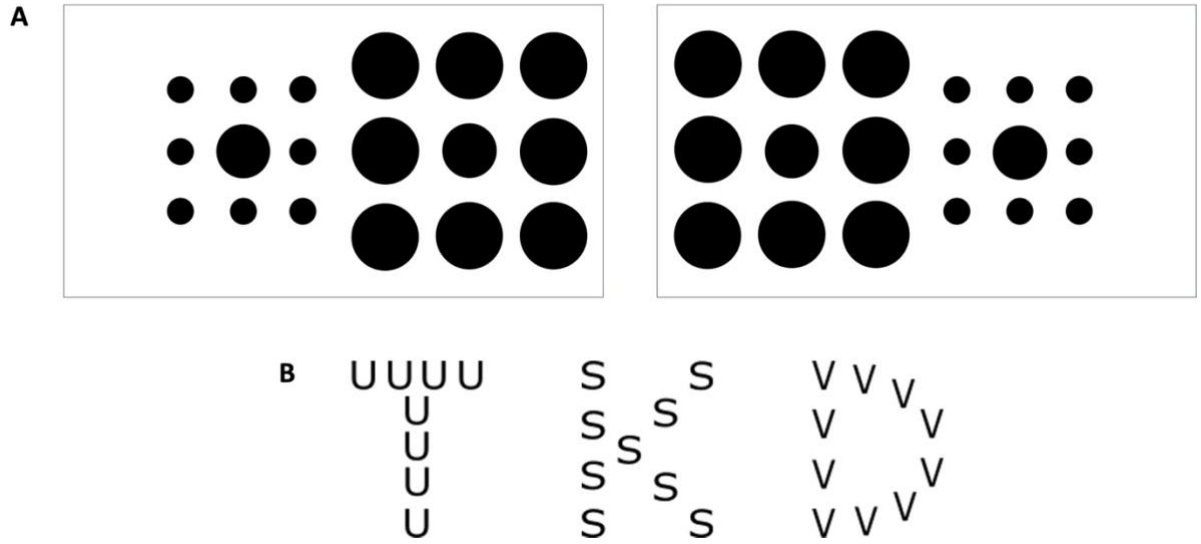
The catch trial stimuli also featured two central circles (surrounded by contextual circles), and one of the two central circles had a fixed diameter of 100 pixels, while the other central circle was either 2 pixels larger (diameter = 102 pixels) or 2 pixels smaller (diameter = 98 pixels). In contrast to the experiment trial stimuli, for the catch trial stimuli,

the larger of the two central circles was surrounded by *smaller* contextual circles (diameter = 50 pixels), and the smaller of the two central circles was surrounded by *larger* contextual circles (diameter = 125 pixels). This configuration of the catch trial stimuli accentuated the perceived size difference between the two central circles. Specifically, the larger of the two central circles appeared larger than its physical size because it was surrounded by contextual circles smaller than itself, whereas the smaller of the two central circles appeared smaller than its physical size because it was surrounded by contextual circles larger than itself. See Figure 5.1A for examples of the Ebbinghaus illusion stimuli for experiment trials and catch trials.

Participants were familiarised with one example of the Ebbinghaus illusion stimulus printed on hardcopy, before beginning the Ebbinghaus illusion task on the computer. There was no computerised practice block. Each trial began with the Ebbinghaus illusion stimuli presented on the screen for up to 5000 ms or until a response was made, followed by a 200 ms inter-trial interval. All trials were presented in a randomised order across participants. Participants were instructed to ignore the contextual circles, and to decide which of the two central circles looked larger. They were informed that the two central circles would never be the same size, and if they were not sure which of the two central circles looked larger, they should take a guess. Participants were instructed to respond as quickly and as accurately as possible, and to press the left arrow key (with their right index finger) to indicate the left central circle looked larger or to press the right arrow key (with their right middle finger) to indicate the right central circle looked larger. Feedback about accuracy was not provided in the Ebbinghaus illusion task.

Figure 5.1

Examples of Stimuli for the Ebbinghaus Illusion Task and the Hierarchical-Figures Task



Note. Row A presents two examples of the Ebbinghaus illusion stimuli used in the present study. The example in the left panel presents an experiment trial stimulus, and the example in the right panel presents a catch trial stimulus. In both examples, the right central circle is physically larger than the left central circle. Row B presents three examples of the hierarchical figures used in the present study. The example on the left presents a global-target figure, with the target 'T' at the global level and 'U' distractors at the local level. The middle example presents a local-target figure, with 'S' targets at the local level and the distractor 'K' at the global level. The example on the right presents a target-absent figure, with the distractor 'D' at the global level and 'V' distractors at the local level.

5.2.3 Statistical Analysis Plan

Our first research question concerned the relationship between the global-local processing bias on the hierarchical-figures task and susceptibility to the Ebbinghaus illusion at the group level. This first question was addressed with two group-level analyses; the first to examine whether there was a local-processing bias in the hierarchical-figures task in older participants compared to young participants (see Part 1 below); the second to examine age-group differences in susceptibility to the Ebbinghaus illusion (see Part 2 below). Our second research question concerned the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion at the individual level. This second question was addressed with an individual-level analysis between the global-local processing bias in the hierarchical-figures task and

susceptibility to the Ebbinghaus illusion (see Part 3 below). Our third research question concerned the relationship between susceptibility to the Ebbinghaus illusion and inspection time of the illusion at both the group level and the individual level. This third question was addressed with a group-level analysis (see Part 2 below) and with an individual-level analysis (see Part 3 below) for susceptibility to the Ebbinghaus illusion and inspection time of the illusion. The statistical analyses comprised of three parts.

Part 1, '*Group-level age-related differences for the global-local processing bias in the hierarchical-figures task*' was a group-level analysis that examined whether there was a local-processing bias in older participants compared to young participants. This bias would be indicated by performance differences between young participants and older participants for the local-target figures compared to the global-target figures in the hierarchical-figures task (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002; also see Chen et al., 2024). Linear mixed-effects models were performed. See Table 5.4 for details of the setup of the linear mixed-effects model in Part 1.

Part 2, 'Group-level age-related differences for susceptibility to the Ebbinghaus illusion and for inspection time of the Ebbinghaus illusion' was a group-level analysis that examined age-group differences between young and older participants in their susceptibility to the Ebbinghaus illusion. Susceptibility to the Ebbinghaus illusion was measured by the point of subjective equality (PSE) and the duration of time spent inspecting the Ebbinghaus illusion (hereafter referred to as 'Inspection Time'). The PSE was calculated as the threshold of percentage size difference at which participants perceived the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles to be of the same size (see Caparos et al., 2012). Higher PSE scores indicated greater susceptibility to the Ebbinghaus illusion, whereas lower PSE scores indicated less susceptibility to the Ebbinghaus illusion. Linear mixed-effects models were performed, with additional Welch's two-sample t tests. See Table 5.4 for details of the setup of the linear mixed-effects model in Part 2.

Table 5.4

Setup for Linear Mixed-Effects Models of the Group-Level Analyses for the Hierarchical-Figures Task and the Ebbinghaus Illusion Task

Setup	Part 1. Hierarchical-figures task	Part 2. Ebbinghaus illusion task
Dependent variable(s)	Reaction Time (ms): for each correct trial in the hierarchical-figures task for each participant	Point of Subjective Equality (PSE): threshold of percentage size difference at which participants perceived the central circle surrounded by larger contextual circles and the central circle surrounded by smaller contextual circles to be of the same size Inspection Time (ms): average inspection time of all correct and incorrect responses for the experiment trials (not including catch trials)
Independent variable(s)	Age Group (young, older) Level (global, local) Visual Field (LVF, RVF)	Age Group (young, older)
Random intercept(s)	Experimenter Participant	Experimenter
Random slopes [a]	Level (global, local) Visual Field (LVF, RVF)	NA

Note. Age Group (young, older), Level (global, local), and Visual Field (LVF, RVF) were deviation coded to obtain an ANOVA-style interpretation of the main effects. LVF = left visual field; RVF = right visual field; NA = not applicable.

[a] For Part 1, the two within-subjects predictors—Level (global, local) and Visual Field (LVF, RVF)—were entered into random slopes to capture dependencies in the repeated-measures design (Barr et al., 2013).

Part 3, 'Individual-level correlations for the global-local processing bias, susceptibility to the Ebbinghaus illusion and inspection time of the Ebbinghaus illusion' was an individual-level analysis that examined individual-level differences in the relationship between the global-local processing bias, susceptibility to the Ebbinghaus illusion and inspection time of the illusion. The Global-Local Index was computed as a measure of the within-individual global-local processing bias in the hierarchical-figures task. This index was calculated as the difference in average RT (ms) between the correct responses to global-target figures compared to local-target figures for each participant. Higher scores on the Global-Local Index indicated a higher degree of within-individual local-processing bias, whereas lower scores on the Global-Local Index indicated a higher degree of within-individual global-processing bias. Pearson correlations were conducted for each of the following three pairs of variables: Global-Local Index, PSE, and Inspection

Time. Additional Pearson partial correlations, controlling for Inspection Time, were conducted for the analyses between the Global-Local Index and PSE. Pearson correlations and Pearson partial correlations were conducted for: (1) age groups combined (i.e., young participants and older participants); (2) young participants only; (3) older participants only. See Table 5.5 for details of the setup of the correlations. To estimate the internal consistency of the variables, Spearman-Brown corrected reliability was computed for the Global-Local Index, PSE and Inspection Time.

All statistical analyses were performed in R Studio (version 2024.09.1+394). The PSE values were computed using the "*glm*" function from the "stats" package. The response variable was the binary data for each trial, indicating whether the central circle surrounded by the larger contextual circles was selected (i.e., selected, not selected). The predictor variable was the percentage size difference between the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles for each trial. The data was fitted with the psychometric function of $p = \phi(\frac{k-d}{\sigma})$, where p was the probability of choosing the central circle surrounded by the larger contextual circles, which equals to 50% at the PSE; $\phi(z)$ was the inverse cumulative distribution function for a standard normal distribution; k was the required threshold for deciding that the central circle surrounded by the larger contextual circles is the larger central circle; d was the percentage size difference between the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles, calculated as $\left(\frac{\text{Size of central circle with larger contextual circles}}{\text{Size of central circle with smaller contextual circles}}\right) \times 100\%$; and σ was the standard deviation of the normally distributed noise (see Caparos et al., 2012).[5] The linear mixed-effects

[5] The constant error (CE) of the present study is defined as $CE = PSE - 100\%$, where 100% represents the reference point at which the two central circles are physically equal in size. In our task, one of the central circles was always fixed at 100 pixels and served as the reference stimulus. Although the design did not include trials where both central circles were physically equal in size, a percentage size difference of 100% represents the hypothetical point at which the two central circles are physically equal in size. Because CE is a linear transformation of PSE, any statistical analysis performed using PSE (e.g., linear mixed-effects models, t tests, and correlations) would yield the same results as if CE had been used. As such, the PSE values computed can be used to measure the magnitude of the Ebbinghaus illusion. We opted to report PSE instead of CE for two reasons. First, Caparos et al. (2012) reported PSE in their analysis for the Ebbinghaus illusion. Second, the present study used the same method of calculating PSE as Caparos et

models were performed using the "*lmer*" function from the "*lme4*" package. Type-III analyses of variance (ANOVA) tables with Wald chi-square tests were obtained using the "*Anova*" function from the "*car*" package. Post hoc pairwise comparisons with Tukey-corrected p values were conducted using the "*emmeans*" function from the "*emmeans*" package. Effect size $d_{\text{mixed-effects}}$ for post hoc pairwise comparisons was computed using the "*eff_size*" function from the "emmeans" package. The Welch's two-sample *t* tests were performed using the "*t.test*" function from the "*stats*" package. Cohen's *d* for Welch's two-sample *t* tests was calculated by dividing the mean difference by the pooled standard deviation. The Pearson correlations were performed using the "*cor*" function from the "*stats*" package. The Pearson partial correlations were performed using the "*pcor.test*" function from the "*ppcor*" package. The confidence intervals for Pearson partial correlations were computed using online codes available on Stack Overflow (Barradas, 2020). Spearman-Brown corrected reliability was computed with 5000 random splits using the "*splithalf*" function from the "*splithalf*" package. For the individual-level analyses between three pairs of variables (Global-Local Index, PSE, Inspection Time), a separate linear regression model was fitted to screen for outliers for each of the two age groups, resulting in a total of six regression models. For each of the six regression models, outliers were identified using four diagnostic plots (standardised residuals plot, Q-Q plot, scale-location plot and Cook's distance plot) generated by the "*plot*" function in R. See Table 5.5 for details of outlier exclusions.

al., allowing for a more direct comparison. This is particularly relevant given that their study was the only previous investigation to examine both group-level and individual-level differences in susceptibility to the Ebbinghaus illusion and global-local processing bias.

Table 5.5

Setup of the Individual-Level Correlations for the Global-Local Processing Bias in the Hierarchical Figures, Susceptibility to the Ebbinghaus Illusion, and Inspection Time in the Ebbinghaus Illusion

Analysis	Type of correlation		Outliers excluded
	Pearson correlation	Pearson partial correlation (Controls for Inspection Time)	
1. Global-Local Index and PSE	√	√	Young = 4, Older = 4
2. Inspection Time and PSE	√	X	Young = 5, Older = 4
3. Global-Local Index and Inspection Time	√	X	Young = 5, Older = 5

Note. PSE = point of subjective equality; √ = conducted; X = not conducted.

5.3 Results

5.3.1 Part 1. Group-Level Age-Related Differences for the Global-Local Processing Bias in the Hierarchical-Figures Task

There were significant main effects for Level ($\chi^2(1) = 70.63$, $p < .001$) and Age Group ($\chi^2(1) = 23.77$, $p < .001$), and significant interactions for Level × Age Group ($\chi^2(1) = 125.11$, $p < .001$) and Level × Visual Field ($\chi^2(1) = 89.72$, $p < .001$). There was no significant main effect for Visual Field ($p = .35$), and no significant interactions for Visual Field × Age Group ($p = .54$) or Level × Visual Field × Age Group ($p = .80$).

Post-hoc pairwise comparisons for the significant Level × Age Group interaction indicated that: (1) young participants demonstrated no RT differences in detecting global targets and local targets, whereas older participants were faster in detecting local targets compared to global targets; (2) young participants were faster in detecting global targets compared to older participants, whereas there were no RT differences between young participants and older participants in detecting local targets.

Post-hoc pairwise comparisons for the significant Level × Visual Field interaction indicated that: (1) global targets were detected faster in the LVF compared to the RVF, and local targets were detected faster in the RVF compared to the LVF; (2) there were no RT differences in detecting global targets and local targets in the LVF whereas, in the RVF, local targets were detected faster compared to global targets. See Table 5.6 for the statistics of the age-related differences for the global-local processing bias, and Figure 5.2 for the estimated marginal means.

Table 5.6

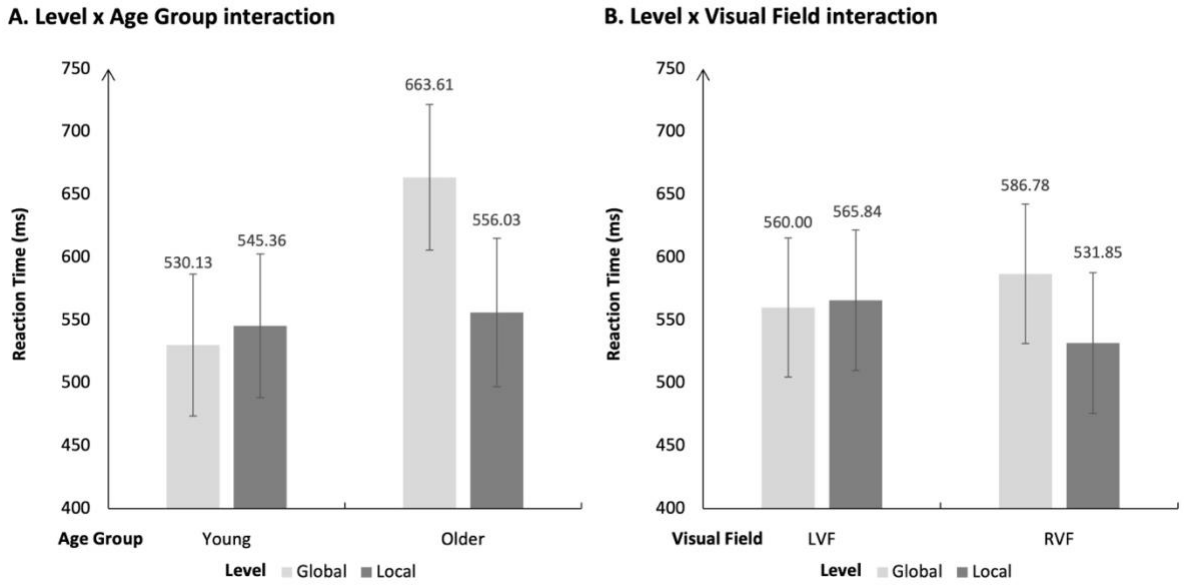
Group-Level Age-Related Differences for the Global-Local Processing Bias in the Hierarchical-Figures Task: Post-Hoc Pairwise Comparisons for the Level × Age Group Interaction and the Level × Visual Field Interaction

Comparison	MD	95% CI	SE	*z*	*p*	$d_{mixed\text{-}effects}$
Level × Age Group interaction						
Young: global – local	–15.27	[–32.68, 2.14]	6.78	–2.25	.11	0.11
Older: global – local	107.55	[85.35, 129.74]	8.64	12.45	< .001***	0.74
Global: young – older	133.48	[95.09, 171.86]	14.94	8.93	< .001***	0.92
Local: young – older	–10.66	[–53.18, 31.86]	16.55	0.64	.92	0.07
Level × Visual Field interaction						
LVF: global – local	15.47	[–1.10, 32.03]	6.45	2.40	.08	0.11
RVF: global – local	76.81	[60.63, 93.00]	6.30	12.20	< .001***	0.53
Global: LVF – RVF	–27.75	[–38.37, –17.13]	4.13	–6.71	< .001***	0.19
Local: LVF – RVF	33.60	[21.15, 46.05]	4.85	6.93	< .001***	0.23

Note. LVF = left visual field; RVF = right visual field; MD = mean differences (ms); CI = confidence intervals; SE = standard errors; *** $p < .001$.

Figure 5.2

Group-Level Age-Related Differences for the Global-Local Processing Bias in the Hierarchical-Figures Task: Estimated Marginal Means for the Level × Age Group Interaction and the Level × Visual Field Interaction



Note. LVF = left visual field; RVF = right visual field. Error bars represent 95% confidence intervals. Panel A presents the estimated marginal means for the significant Level × Age Group interaction (collapsed across visual fields). Panel B presents the estimated marginal means for the significant Level × Visual Field interaction (collapsed across age groups).

5.3.2 Part 2. Group-Level Age-Related Differences for Susceptibility to the Ebbinghaus Illusion and for Inspection Time of the Ebbinghaus Illusion

Both the linear mixed-effects models and the Welch's two-sample *t* tests indicated that there were no group-level differences between young participants and older participants in either: (1) susceptibility to the Ebbinghaus illusion; or (2) inspection time of the Ebbinghaus illusion. See Table 5.7 for the statistics of the age-related differences for susceptibility to the Ebbinghaus illusion and inspection time of the Ebbinghaus illusion, and Figure 5.3 for the estimated marginal means.

Table 5.7

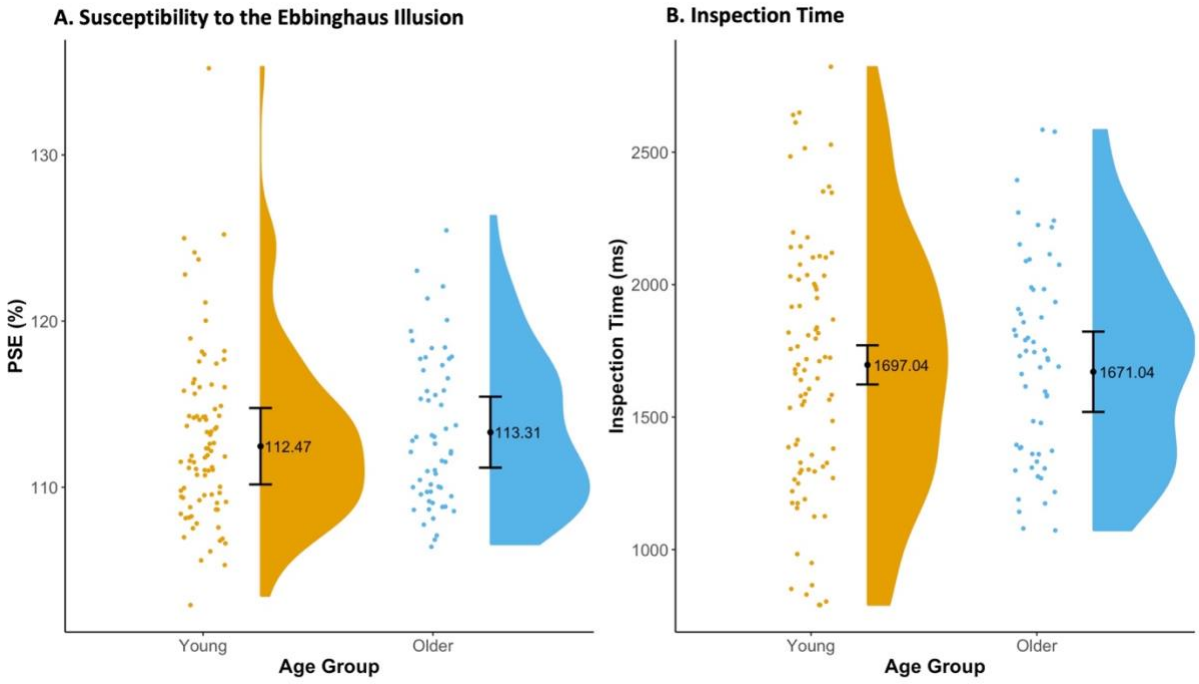
Group-Level Age-Related Differences for Susceptibility to the Ebbinghaus Illusion and for Inspection Time of the Ebbinghaus Illusion: Results for the Linear Mixed-Effects Models and Welch's Two-Sample T *Tests*

Analysis comparing two age groups	$MD_{young-older}$, 95% CI	*t*	*df*	*p*	$d_{mixed-effects}$ / *d*
Susceptibility to the Ebbinghaus illusion (PSE)					
Linear mixed-effects model	0.85, [–1.19, 2.88]	1.18	113.79	.41	0.17
Welch's two-sample *t* test		0.46	130.98	.65	0.08
Inspection Time (ms)					
Linear mixed-effects model	–26.00, [–229.26, 177.26]	–0.27	13.95	.79	0.06
Welch's two-sample *t* test		–0.36	139.05	.72	0.06

Note. MD = mean differences; CI = confidence intervals.

Figure 5.3

Group-Level Age-Related Differences for Susceptibility to the Ebbinghaus Illusion and for Inspection Time of the Ebbinghaus Illusion: Estimated Marginal Means for Young Participants and Older Participants



Note. PSE = point of subjective equality. PSE represents the threshold of percentage size difference (i.e., $\left(\frac{\text{Size of central circle with larger contextual circles}}{\text{Size of central circle with smaller contextual circles}}\right) \times 100\%$) at which participants perceived the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles to be of the same size. Error bars represent 95% confidence intervals, and dots represent the data for each participant. Panel A presents the estimated marginal means for PSE. Panel B presents the estimated marginal means for Inspection Time.

5.3.3 Part 3. Individual-Level Correlations for the Global-Local Processing Bias, Susceptibility to the Ebbinghaus Illusion and Inspection Time of the Ebbinghaus Illusion

Individual-level correlations were conducted between three pairs of variables: Global-Local Index and PSE, Inspection Time and PSE, and Global-Local Index and Inspection Time. For each pair of variables, three analyses were conducted—for the two age groups combined, for young participants only, and for older participants only.

For the relationship between the Global-Local Index and PSE, there were significant positive Pearson correlations and significant positive Pearson partial correlations after controlling for inspection time in the analyses for the two age groups combined, for only the young participants, and for only the older participants. These findings indicated that participants with the higher degree of within-individual local-processing bias were the participants who were *more* susceptible to the Ebbinghaus illusion.

For the relationship between Inspection Time and PSE, there were significant negative Pearson correlations for the analyses of the two age groups combined, the older participants only, and the young participants only. These findings indicated that the participants who spent a longer time inspecting the Ebbinghaus illusion were the participants who were less susceptible to the Ebbinghaus illusion.

For the relationship between the Global-Local Index and Inspection Time, there were no significant Pearson correlations for the analyses of the two age groups combined, the older participants only, or the young participants only. These findings indicated that the amount of time participants spent inspecting the Ebbinghaus illusion was not related to their within-individual global-local processing bias. See Table 5.8Table 5.8 for the statistics of the individual-level correlations for the global-local processing bias, susceptibility to the Ebbinghaus illusion and inspection time of the Ebbinghaus illusion, Table 5.9 for the Spearman-Brown corrected reliability for each variable in the individual-level correlations, and Figure 5.4 for illustrations of the individual-level correlations.

Table 5.8

Individual-Level Correlations for the Global-Local Processing Bias, Susceptibility to the Ebbinghaus Illusion and Inspection Time of the Ebbinghaus Illusion

Analysis	All participants				Young participants				Older participants			
	r/ $r_{partial}$, 95% CI	*t*	*df*	*p*	*r*/ $r_{partial}$, 95% CI	*t*	*df*	*p*	*r*/ $r_{partial}$, 95% CI	*t*	*df*	*p*
Global-Local Index and PSE												
Pearson correlation	.26, [.09, .41]	3.09	135	.002**	.25, [.04, .44]	2.34	81	.02*	.36, [.10, .57]	2.77	52	.008**
Pearson partial correlation	.26, [.10, .41]	3.18	135	.002**	.28, [.07, .47]	2.62	81	.01*	.34, [.07, .55]	2.54	52	.01*
Inspection Time and PSE												
Pearson correlation	–.46, [–.58, –.32]	–6.03	134	< .001***	–.46, [–.62, –.27]	–4.64	80	< .001***	–.48, [–.66, –.24]	–3.92	52	< .001***
Global-Local Index and Inspection Time												
Pearson correlation	–.002, [–.19, .15]	–0.28	133	.78	.07, [–.15, .28]	0.65	80	.52	–.24, [–.48, .03]	–1.78	51	.08

Note. PSE = point of subjective equality; CI = confidence intervals; * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5.9

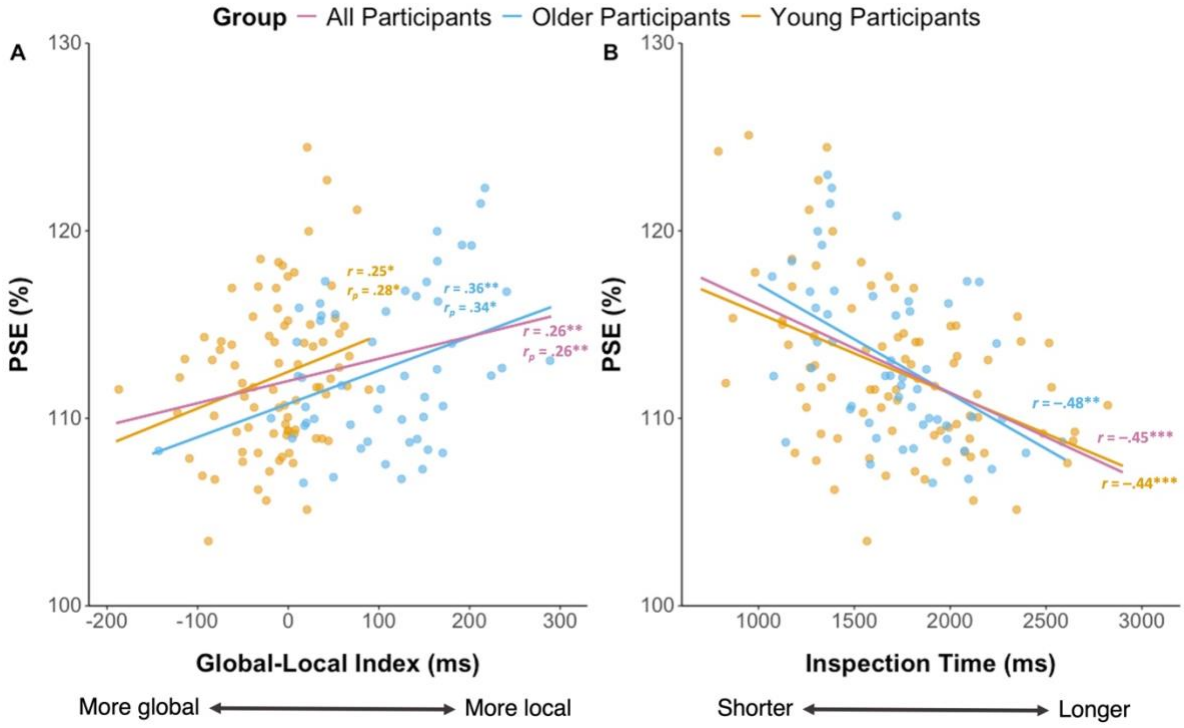
Spearman-Brown Corrected Reliability Estimates for the Global-Local Processing Bias, Susceptibility to the Ebbinghaus Illusion and Inspection Time of the Ebbinghaus Illusion

Analysis		All participants	Young participants	Older participants
1	Global-Local Index/ PSE	.88, [.84, .91] / .87, [.84, .90]	.71, [.60, .80] / .87, [.83, .91]	.82, [.74, .89] / .87, [.81, .91]
2	Inspection Time/ PSE	.97, [.96, .98] / .86, [.83, .89]	.97, [.96, .98] / .86, [.81, .90]	.96, [.93, .97] / .87, [.82, .92]
3	Inspection Time/ Global-Local Index	.96, [.95, .97] / .88, [.85, .91]	.97, [.96, .98] / .70, [.59, .79]	.95, [.93, .97] / .82, [.73, .89]

Note. PSE = point of subjective equality. Numbers in square brackets represent 95% confidence intervals. There were 137 participants (83 young participants, 54 older participants) in Analyses 1, 136 participants (82 young participants, 54 older participants) in Analyses 2, and 135 participants (82 young participants, 53 older participants) in Analyses 3.

Figure 5.4

Individual-Level Correlations between the Global-Local Processing Bias and Susceptibility to the Ebbinghaus Illusion, and between Inspection Time of the Illusion and Susceptibility to the Ebbinghaus Illusion



Note. PSE = point of subjective equality; PSE represents the threshold of percentage size difference (i.e., $\left(\frac{\text{Size of central circle with larger contextual circles}}{\text{Size of central circle with smaller contextual circles}}\right) \times 100\%$) at which participants perceived the central circle surrounded by the larger contextual circles and the central circle surrounded by the smaller contextual circles to be of the same size. *r* = Pearson correlations, r_p = Pearson partial correlations controlling for Inspection Time; * $p < .05$, ** $p < .01$, *** $p < .001$. The dots represent the data of individual participants. Panel A presents the results of the correlations between the Global-Local Index and PSE. Higher scores on the Global-Local Index indicate a higher degree of within-individual local-processing bias, lower scores indicate a higher degree of within-individual global-processing bias. Higher scores on PSE indicate greater susceptibility to the Ebbinghaus illusion, lower scores on PSE indicate reduced susceptibility to the Ebbinghaus illusion. Panel B presents the results for the correlations between Inspection Time and PSE.

5.4 Discussion

Susceptibility to the Ebbinghaus illusion has been proposed to be modulated by the relative bias for global processing *versus* local processing, such that a bias for local processing reduces susceptibility to the Ebbinghaus illusion, whereas a bias for global processing increases susceptibility to the Ebbinghaus illusion (Happé, 1996). While in previous research, the Ebbinghaus illusion has been used extensively to measure and interpret group-level differences in the global-local processing bias (e.g., Phillips et al., 2004; Doherty et al., 2008), questions remained regarding whether the Ebbinghaus illusion can account for individual-level differences in the global-local processing bias. In the present study, we examined systematically the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion at both the group level (i.e., young adults *versus* older adults) and at the individual level. Navon's (1977) hierarchical-figures task was used to measure the global-local processing bias, and the Ebbinghaus illusion task was used to measure susceptibility to the illusion.

Our findings provide three key insights for age-related changes and the role of individual differences in the perception of the Ebbinghaus illusion. First, at the group level, older participants (as compared to young participants) demonstrated worse performance for global processing in the hierarchical-figures task, but there were no differences in susceptibility to the Ebbinghaus illusion between the two age groups. Second, at the individual level, the participants with the stronger within-individual local-processing bias were the participants who demonstrated *greater* susceptibility to the Ebbinghaus illusion. Third, also at the individual level, the participants with longer inspection times for the Ebbinghaus illusion were the participants who demonstrated reduced susceptibility to the illusion.

5.4.1 Global-Local Processing Bias and Susceptibility to the Ebbinghaus Illusion at the Group Level

In response to our first research question concerning the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion at the group level, we found that older participants (as compared to young participants)

demonstrated worse performance for global processing in the hierarchical-figures task, but that these age-related differences in global processing were not associated with reduced susceptibility to the Ebbinghaus illusion. Our group-level findings for the hierarchical-figures task (see Results, Part 1) are consistent with two previously reported findings that indicate differences in the global-local processing bias between young adults and older adults. When comparing within each age group, older adults were faster at local processing compared to global processing (i.e., a within-group local-processing bias in older adults), whereas young adults did not demonstrate performance differences between global processing and local processing (Chen et al., 2024; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999). When comparing between age groups, older adults were slower at global processing compared to young adults, whereas there were no age group differences in local processing (Chen et al., 2024). Our findings, along with previous findings by Chen et al., indicate that age-group differences in the global-local processing bias are driven by older adults' performance, which was worse for global processing than for local processing.

Our group-level findings for the Ebbinghaus illusion task (see Results, Part 2) indicate that there were no differences in susceptibility to the illusion between young participants and older participants. These findings are not consistent with previously reported findings; for example, Wapner et al. (1960) and Mazuz et al. (2024) reported reduced susceptibility to the Ebbinghaus illusion in older adults compared to young adults. However, consideration needs to be given to the fact that there are methodological differences that may account for these inconsistent findings. First, both Wapner et al. and Mazuz et al. adopted a circular configuration for the contextual circles in the Ebbinghaus illusion stimuli; in the present study, we adopted a square configuration for the contextual circles. Second, neither Wapner et al. nor Mazuz et al. accounted for the potential effects of mild cognitive impairment on overall task performance in older adults (e.g., Álvarez-San Millán et al., 2022); in the present study, we screened for cognitive functioning in older participants using the MoCA (Nasreddine, 1996).

Overall, our group-level findings indicate that, while older adults demonstrate worse performance for global processing compared to young adults, participants in the two age groups did not differ in their susceptibility to the Ebbinghaus illusion. These group-level findings do not provide support for Happé's (1996) visual attentional integration theory, which posits that group-level differences in the global-local processing bias can account for susceptibility to the Ebbinghaus illusion.

Concerns have been raised previously about the practice of using the Ebbinghaus illusion to measure group-level differences in the global-local processing bias. Several studies (Manning et al., 2017; Roper & Mitchell, 1999; Roper & Mitchell, 2001) have failed to replicate Happé's (1996) original findings of reduced susceptibility to the Ebbinghaus illusion in children on the autistic spectrum compared to typically developing children. These researchers found no differences in susceptibility to the Ebbinghaus illusion between the two groups, despite the proposal that children on the autistic spectrum would demonstrate a local-processing bias due to a weakened central coherence (Shah & Frith, 1983; Shah & Frith, 1993). Several methodological differences may account for the inconsistent group-level findings for susceptibility to the Ebbinghaus illusion in children on the autistic spectrum. In the study by Happé, the Ebbinghaus illusion stimuli were presented for one trial on a hard copy, and the viewing distance was not controlled. Whereas in the studies that failed to replicate Happé's (1996) original findings, there were multiple trials with the Ebbinghaus illusion stimuli (see Manning et al.: 80 trials in Experiment 1; Roper and Mitchell: 10 trials in Experiment 1; Roper and Mitchell: 6 trials), and these were presented with a fixed viewing distance on a computer screen. Taken together, these previous findings, combined with group-level findings in the present study, suggest that the relationship between susceptibility to the Ebbinghaus illusion and the global-local processing bias at the group level may be more nuanced than initially proposed.

5.4.2 Global-Local Processing Bias and Susceptibility to the Ebbinghaus Illusion at the Individual Level

In response to our second research question, concerning the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion at the individual level, we investigated the extent to which the global-local processing bias accounts for susceptibility to the Ebbinghaus illusion at the individual level. We found (see Results, Part 3) that the young participants and older participants with the stronger within-individual local-processing bias (i.e., faster detection of the local level compared to the global level) in the hierarchical-figures task were the participants who demonstrated *greater* susceptibility to the Ebbinghaus illusion. These findings were unexpected as they do not provide support for Happé's (1996) visual attentional integration theory, which predicts that a stronger local-processing bias will lead to reduced susceptibility to the Ebbinghaus illusion.

To the best of our knowledge, only Caparos et al. (2012) have examined individual-level differences in the global-local processing bias using both the hierarchical-figures task and the Ebbinghaus illusion. While their findings also do not provide support for Happé's (1996) visual attentional integration theory, they found no significant correlation between the within-individual global-local processing bias and susceptibility to the illusion. The inconsistent individual-level findings between the present study and those of Caparos et al. may stem from several methodological differences in the hierarchical-figures task. First, the present study employed a divided-attention task, where one hierarchical figure was presented per trial, and participants attended simultaneously to the global level and local level of the hierarchical figure. In contrast, Caparos et al. employed a similarity-matching task, where three hierarchical figures were presented per trial, and participants chose which of two hierarchical figures was most like the third hierarchical figure (see Footnote 1). Second, the present study used RT as the measure, whereas Caparos et al. used percentage (of choosing one out of the two hierarchical figures). Given the limited research examining individual-level differences in the global-local processing bias and susceptibility to the Ebbinghaus illusion, future research is

warranted to examine systematically the methodological differences in how this hierarchical-figures task influences the individual-level relationship.

5.4.3 Susceptibility to the Ebbinghaus Illusion and Inspection Time of the Illusion at the Group Level and at the Individual Level

In response to our third research question concerning susceptibility to the Ebbinghaus illusion and inspection time, we found that although the young and older age groups did not differ in their inspection time of the Ebbinghaus illusion, individual participants (both young and older) with the longer inspection times for the Ebbinghaus illusion were the participants who demonstrated reduced susceptibility to the illusion. Our group-level findings (see Results, Part 2) indicated there were no differences between the two age groups for either susceptibility to the Ebbinghaus illusion or inspection time of the illusion. Our individual-level findings (see Results, Part 3) indicated that the young and older participants who spent a longer time inspecting the Ebbinghaus illusion were the participants who were less susceptible to the Ebbinghaus illusion. These findings for young participants are consistent with the studies by Bressan and Kramer (2013, 2021), who reported that young adults with longer inspection times were less susceptible to the Ebbinghaus illusion. Our study is the first to extend these individual-level findings to older adults, demonstrating that longer inspection times are associated with reduced susceptibility to the Ebbinghaus illusion for both young and older age groups. Additionally, we demonstrated that the amount of time individual participants (both young and older participants) spent inspecting the Ebbinghaus illusion was not related to their global-local processing bias as demonstrated in the hierarchical-figures task.

Bressan and Kramer (2013) have proposed that shorter inspection times induce a global-processing bias during the Ebbinghaus illusion task, while longer inspection times induce a local-processing bias. Therefore, although shorter inspection times can facilitate rapid size judgements, they also increase susceptibility to the illusion. Whereas longer inspection times enable detailed size judgements, which can reduce susceptibility to the illusion. Intriguingly, this proposal implies that the global-local processing bias can be modulated by the stimulus inspection time adopted in different

experiment paradigms. An individual may demonstrate a stronger local-processing bias in an experiment that allows for longer stimulus inspection time, whereas the same individual may demonstrate a stronger global-processing bias in another experiment that has a shorter stimulus inspection time. In the present study, we examined the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion using two different experiment paradigms. To measure the global-local processing bias, we employed Navon's (1977) hierarchical-figures task, which had a constant stimulus inspection time of 150 ms. To measure susceptibility to the Ebbinghaus illusion, we employed the Ebbinghaus illusion task, in which stimulus inspection time could vary across trials as stimuli were presented on the screen until a response was made. When participants take a longer time to inspect the Ebbinghaus illusion stimuli, they may demonstrate a stronger within-individual local-processing bias in the Ebbinghaus illusion task compared to their global-local processing performance in the hierarchical-figures task. Conversely, when participants take a shorter time to inspect the Ebbinghaus illusion stimuli, they may demonstrate a stronger within-individual global-processing bias in the Ebbinghaus illusion task compared to their global-local processing performance in the hierarchical-figures task. Therefore, the global-local processing bias as measured by Navon's hierarchical-figures task in the present study may not represent participants' global-local processing bias during the Ebbinghaus illusion task.

Bressan and Kramer's (2013) proposal provides a plausible explanation for our group-level findings regarding susceptibility to the Ebbinghaus illusion and inspection time of the illusion. In the present study, the young and older participants did not differ either in their susceptibility to the Ebbinghaus illusion nor in their average inspection time of the illusion, even though their inspection time could vary across trials—the stimuli were presented on the screen until a response was made. These findings can be interpreted to mean that the two age groups did not differ in susceptibility to the Ebbinghaus illusion because, at the group level, they did not differ in their relative bias for global processing *versus* local processing during the Ebbinghaus illusion task. However, Bressan and Kramer's proposal does not explain the findings of Mazuz et al. (2024), in which the older participants demonstrated reduced susceptibility to the Ebbinghaus

illusion compared to young participants. In Mazuz et al.'s study, the Ebbinghaus illusion stimuli were presented for a fixed duration on each trial, therefore there could be no differences demonstrated by the participants in regard to the length of inspection time of the illusion. The inconsistent findings between the present study and Mazuz et al. highlight the need for future research to compare systematically the presentation time of the Ebbinghaus illusion, a comparison between fixed stimulus duration (e.g., Bressan & Kramer, 2021; Mazuz et al., 2024) and unlimited stimulus duration (e.g., Phillips et al., 2004) in young and older adults.

5.4.4 Theoretical Considerations

Happé's (1996) visual attentional integration theory proposes that the Ebbinghaus illusion arises when the central circle and the contextual circles are integrated and processed globally, as a whole configuration. But there are ongoing debates concerning the mechanism underlying the Ebbinghaus illusion. In addition to the visual attentional integration theory, there are two major theories that provide alternative explanations for the Ebbinghaus illusion: the constancy scaling theory and the contouring interaction theory. Supporters of the constancy scaling theory argue that the Ebbinghaus illusion arises from misinterpreting contextual circles as depth cues, with larger contextual circles perceived as closer and smaller contextual circles perceived as farther away (Day, 1972; Gregory, 1963). Ropar and Mitchell (2001) suggested that both depth perception and global-local processing mechanisms may contribute to the perception of the Ebbinghaus illusion, thus making it difficult to isolate the specific effects of the global-local processing bias when using the illusion as a measure.

Recent studies favour the contouring interaction theory, which proposes that the Ebbinghaus illusion arises from retinal-neural interaction occurring at a lower level, before the involvement of visual attention or cognition (e.g., Eriksson, 1970; Jaeger & Klahs, 2015; Rose & Bressan, 2002; Sherman & Chouinard, 2016; Takao et al., 2019; Todorović & Jovanović, 2018). This theory suggests that the neural representation of the Ebbinghaus illusion is modulated by the relative retinal distance between the contours of the central circle and the contextual circles. A plausible implication of the contouring

interaction theory is that susceptibility to the Ebbinghaus illusion should remain constant across individuals and groups who have healthy retinal and neural structures, given the proposal that the illusion arises at a lower level. Our group-level findings were consistent with this implication—there were no differences in susceptibility to the Ebbinghaus illusion between our young participants and older participants, all of whom had normal or corrected-to-normal vision and no history of self-reported neurological impairments. However, this interpretation warrants careful consideration, as ageing is associated with various changes in retinal structures (see Bonnel et al., 2003, for a review), and the specific retinal-neural mechanisms underlying the Ebbinghaus illusion remain unclear. Additionally, the contouring interaction theory cannot fully account for our individual-level findings, which indicate that susceptibility to the Ebbinghaus illusion can be modulated by the duration of time spent inspecting the illusion. Future research is warranted to investigate the influence of age-related retinal changes and inspection time on the perception of the Ebbinghaus illusion at the stage of retinal-neural interactions.

In contrast, Kirsch and Kunde (2021) suggested a more nuanced account of the Ebbinghaus illusion, indicating that susceptibility to the Ebbinghaus illusion is modulated by a combination of factors. In particular, Kirsch and Kunde reported two perceptual factors that independently modulate susceptibility to the Ebbinghaus illusion: spatial extent (i.e., the size of the overall Ebbinghaus illusion configuration) and spatial frequency (i.e., the size of the contextual circles). These findings indicated that susceptibility to the Ebbinghaus illusion is unlikely to be fully explained by a single mechanism, such as the global-local processing bias, constancy scaling, or contouring interaction. Instead, it is influenced by a combination of multiple factors. This underscores the need for caution when using this illusion to interpret group-level or individual-level differences in a single mechanism, such as the global-local processing bias. Future research is warranted to manipulate these different factors systematically, and to clarify their independent effects on the perception of the Ebbinghaus illusion.

5.5 Conclusion

Our study was the first to examine both the age-group differences and the individual-level differences in young and older adults' perception of the Ebbinghaus illusion. Our results for the group-level differences between young adults and older adults indicate that healthy ageing does not affect susceptibility to the Ebbinghaus illusion, but that healthy ageing does affect the global-local processing bias when measured with the hierarchical-figures task. The older adults' performance was worse for global processing than for local processing—local processing remained intact in older participants, and it did not differ from that of young adults. Our results for the individual-level differences within young adults and older adults indicate that, regardless of age group, an individual's relative attentional processing bias (global-processing bias *versus* local-processing bias) plays an important role in the perception of the Ebbinghaus illusion. The individuals with the stronger local-processing bias on the hierarchical-figures task were the individuals who were more susceptible to the Ebbinghaus illusion. Overall, our results reveal there is a nuanced relationship between the visual attentional mechanisms of global-local processing and susceptibility to the Ebbinghaus illusion. Contrary to Happé's proposal, a bias for local processing is not associated with reduced susceptibility to the Ebbinghaus illusion at either the group level or the individual level. Our results also highlight valid concerns that have been made regarding using the Ebbinghaus illusion as the sole measure for examining differences in the global-local processing bias, and suggest that future studies should employ multiple experiment paradigms when examining these differences. Further research is warranted to investigate the theoretical underpinnings of the Ebbinghaus illusion and its broader implications for visual attention across the life span.

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Chapter 6 General Discussion

The two hemispheres of the human brain demonstrate hemispheric asymmetry for global-local processing, with global processing (attending to an overall scene) specialised in the right hemisphere and local processing (attending to the finer details in the scene) specialised in the left hemisphere. Age-related changes in the functional organisation of the brain in neurologically healthy individuals may affect these visual attentional processes. This thesis was an investigation of how healthy ageing influences global-local processing, with two overall aims. The first aim was to understand how healthy ageing influences the allocation of visual attention to the global level and to the local level of visual information. The second aim was to understand how healthy ageing influences the hemispheric asymmetry underlying global-local processing.

Chapter 1 presents a literature review of the history of hemispheric asymmetry research, emphasising four key aspects of hemispheric asymmetry: (1) Why does the human brain demonstrate hemispheric asymmetry? (2) Does hemispheric asymmetry change across the lifespan? (3) Does hemispheric asymmetry vary across individuals? and (4) What are the theoretical interpretations of these hemispheric asymmetry findings? Chapter 2 presents an empirical study investigating whether hemispheric asymmetry for global-local processing is affected by stimulus category and by healthy ageing. Chapter 3 presents an empirical study investigating whether there are age-related differences in attentional orienting for global-local processing. Chapter 4 presents an empirical study investigating individual differences in hemispheric asymmetry for global-local processing in right-handed young and older adults, and whether such individual differences can account for age-related difficulties in global processing. Chapter 5 presents an empirical study investigating age-related differences and individual differences in the perception of the Ebbinghaus illusion, and the association between susceptibility to the illusion and global-local processing.

In this Chapter, I discuss four key findings derived from the empirical studies in this thesis:

1. Healthy ageing influences not only the ability to process global-level information but also the ability to re-orient attention to global-level information;
2. Hemispheric asymmetry for global-local processing remains intact with age.
3. Evidence for the right-hemisphere ageing hypothesis is mixed;
4. Individual differences in behavioural measures for global-local processing.

6.1 Healthy Ageing Influences Not Only the Ability to Process Global-Level Information but also the Ability to Re-Orient Attention to Global-Level Information

Healthy ageing is related to changes in many aspects of visual attention, including global-local processing. Widely reported behavioural studies using Navon's (1977) hierarchical figures have indicated an age-related local-processing bias in older adults. This processing bias is characterised by older adults demonstrating better performance for detecting local stimuli compared to global stimuli, whereas young adults demonstrate either no performance differences in detecting global stimuli and local stimuli (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999) or better performance in detecting global stimuli compared to local stimuli (Slavin et al., 2002). This thesis examined these age-related changes in global-local processing by addressing two important gaps in the literature:

1. Is the local-processing bias found in older adults driven by an age-related improvement in local processing or an age-related difficulty with global processing?
2. Are there age-related differences in attentional orienting for global-local processing?

6.1.1 Is the Local-Processing Bias Found in Older Adults Driven by an Age-Related Improvement in Local Processing or an Age-Related Difficulty with Global Processing?

Previous studies have reported a local-processing bias in older adults (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Slavin et al., 2002). These results were based on within-group findings—comparing whether performance for global stimuli differs from that for local stimuli within the young adult group and within the older adult group. However, none of these studies have reported between-groups findings—comparing whether the young adult group and the older adult group differ in performance for global stimuli, and whether the two age groups differ in performance for local stimuli. One reason for this lack of report on between-groups findings may have derived from a research focus concerning how ageing influences the global precedence effect (see Bruyer & Scailquin, 2000). Specifically, this line of research assumes that, in young adults, visual attention proceeds from global processing to local processing, such that better performance for global stimuli compared to local stimuli (i.e., a global-processing bias) is taken as evidence for the global precedence effect (Navon, 1977; also see Chapter 4 for previous evidence that challenged this interpretation). In other words, this line of research concerns how healthy ageing influences the temporal 'primacy' or 'superiority' of global processing over local processing, rather than concerning how the two age groups differ in the efficiency of global processing and in the efficiency of local processing, as two independent cognitive components. Consequently, the question remained as to whether the observed age-related local-processing bias stemmed from older adults demonstrating better performance in detecting local stimuli compared to young adults, or from older adults demonstrating worse performance in detecting global stimuli compared to young adults.

To examine this, the empirical studies presented in Chapters 2, 4, and 5 adopted a divided-attention task and a Go/No-go response mode, in which neurologically healthy young and older participants were required to attend to the global level and local level of the hierarchical figures concurrently and make responses to a target that could randomly appear at either the global level or the local level. Findings from these three empirical studies indicate there is strong evidence that older adults demonstrate an age-related

worse performance in global processing, whereas local processing remains intact with age. Specifically, our within-group findings for reaction time support previous findings (Insch et al., 2012; Lux et al., 2008; Oken et al., 1999) that older participants demonstrated slower response times in detecting global stimuli compared to local stimuli, whereas young participants demonstrated no reaction time differences in detecting global stimuli and local stimuli. Importantly, our between-groups findings for reaction time indicate that older participants were slower in detecting global stimuli compared to young participants, whereas the two age groups did not demonstrate performance differences in detecting local stimuli. The only exception was observed in Chapter 2, when the stimulus category 'letter' was adopted. Both young and older participants were faster in detecting local letters compared to global letters, and young participants were faster in detecting both global letters and local letters compared to older participants. It should be noted that Chapters 4 and 5, in which the stimulus category of letter was also adopted, involved larger sample sizes (Chapter 4: young = 127, older = 58; Chapter 5: young = 87, older = 58) compared to Chapter 2 (young = 27, older = 34). The findings from Chapters 4 and 5 were consistent with the overall pattern observed throughout this thesis: there is an age-related worse performance in global processing, but local processing remains intact with age. See Table 6.1 for a summary of the findings for age-related changes in global-local processing in Chapters 2, 4, and 5.

Table 6.1

Summary of Reaction Time Findings Regarding Age-Related Changes in Global-Local Processing

Chapter	Young *n*	Older *n*	Stimulus category	Within-group comparison		Between-groups comparison	
				Young	Older	Global	Local
	27	34	Letter	global > local	global > local	young < older	young < older
Chapter 2	27	32	VO	global = local	global > local	young < older	young = older
	27	30	NVS	global = local	global > local	young < older	young = older
Chapter 4	127	58	Letter	global = local	global > local	young < older	young = older
Chapter 5	87	58	Letter	global = local	global > local	young < older	young = older

Note. Symbols indicate the direction and significance of reaction time differences: '>' denotes significantly slower reaction time; '<' denotes significantly faster reaction time; and '=' denotes no significant reaction time difference. VO = verbalisable object, NVS = nonverbalisable shape.

These findings have both theoretical and practical implications. In regards to the theoretical implications, although previous studies (Agnew et al., 2016; Bruyer & Scailquin, 2000; Bruyer et al., 2003; Georgiou-Karistianis et al., 2006; Insch et al., 2012; Lux et al., 2008; Oken et al., 1999; Roux & Ceccaldi, 2001; Slavin et al., 2002) have established that healthy ageing influences global-local processing, some of these studies (e.g., Bruyer & Scailquin, 2000; Bruyer et al., 2003) conceptualised global-local processing as a cognitive style, describing how visual attention proceeds from one processing level to the other processing level along a continuum. With findings of a global-processing bias (i.e., better performance for global processing compared to local processing) positioned at one end of the continuum, indicating that global processing precedes local processing (i.e., a global-precedence effect) and, findings of a local-processing bias (i.e., better performance for local processing compared to global processing) positioned at the other end of the continuum, indicating that local processing precedes global processing (i.e., a local-precedence effect). Accordingly, these studies proposed that young and older adults are positioned at different points of this continuum, with young adults demonstrating a stronger global precedence effect and older adults demonstrating a stronger local precedence effect. Our findings, however, indicate that healthy ageing does not influence global-local processing as a single cognitive style. Rather, global processing and local processing are two independent cognitive components, which are differentially affected by healthy ageing. It is the component of global processing that demonstrates the greater age-related changes, whereas the component of local processing remains relatively intact with age.

In regard to the practical implications, our between-groups comparisons (between the young group and older group) established that local processing is an important baseline: healthy ageing does not influence performance for local processing, but global processing is worse in older adults compared to young adults. These findings have potential diagnostic value, as identifying whether healthy ageing influences global processing or local processing provides an important reference point for interpreting impairments in visual attention associated with age-related neurodegenerative conditions. For example, including a global-local processing task into clinical

assessments could help differentiate healthy ageing from pathological ageing, such as Alzheimer's disease (see Álvarez-San Millán et al., 2022).

6.1.2 Are there Age-Related Differences in Attentional Orienting for Global-Local Processing?

As mentioned in the last subsection (Section 6.1.1), previous studies investigating the influence of healthy ageing on global-local processing conceptualised global-local processing as a single cognitive style, concerning the extent to which visual attention proceeds from global processing to local processing. This conceptualisation not only ignores how healthy ageing influences global processing and local processing (as two independent cognitive components) but also overlooks the complex dynamic between global processing and local processing. Notably, the assumption underlying the global-precedence effect or local-precedence effect is that visual attention operates in a one-way manner, starting sequentially from processing one level to processing the other level. In reality, however, individuals must constantly orient attention back and forth between the global level and the local level of a complex visual scene. For example, when driving on a busy street, attention alternates between the overall driving environment (i.e., the global level) and focusing on specific details, such as checking a traffic light or noticing a cyclist approaching from the side (i.e., the local level). A literature gap existed in regard to whether healthy ageing also influences the ability to disengage attention and re-orient attention for global-local processing.

The empirical study presented in Chapter 3 is the first study in the field to examine this literature gap. A focused-attention task and a Yes/No detection-response mode were adopted, in which participants were required to focus on one processing level of the hierarchical figure (i.e., either the global level *or* the local level) and were instructed to detect whether a target appeared at the task-relevant level. The participants' 'Yes' responses indicated that a target appeared at the task-relevant level, while their 'No' response indicated that a target did not appear at that task-relevant level. Attentional orienting for global-local processing was introduced by having the target appear at the task-irrelevant level, while the distractor appeared at the task-relevant level. Participants' attention would first be drawn to the target that appeared at the task-

irrelevant level, and they then needed to disengage attention from this task-irrelevant level and re-orient attention back to the task-relevant level to make a correct 'No' response. There were two key findings.

First, healthy ageing relates to greater difficulties in disengaging attention from the local level for the purpose of re-orienting attention to the global level (compared to disengaging attention from the global level for the purpose of re-orienting attention to the local level). Specifically, older participants were slower in making 'No' responses when a target appeared at the task-irrelevant local level, compared to making 'No' responses when a target appeared at the task-irrelevant global level. For young participants, there were no performance differences between these two 'No' response conditions, indicating that young participants demonstrated comparable performance for disengaging attention from the global level and from the local level.

Second, when instructed to focus on the global level, older participants were slower in making 'No' responses when a target appeared at the task-irrelevant local level compared to when no target appeared at either level, indicating that the presence of target information at the local level may lead to a shift of attention away from the global level. In contrast, when instructed to focus on the local level, older participants did not demonstrate reaction time differences in making 'No' responses between the condition when a target appeared at the task-irrelevant global level and the condition when no target appeared at either level. These findings indicate that the presence of target information at the global level did not lead to a shift of attention away from the local level.

The findings from Chapter 3 have two significant theoretical implications. The first implication relates to the right-hemisphere ageing hypothesis. Guilbert et al. (2019) used a spatial-cueing paradigm and found that healthy ageing relates to difficulties with the directional component of attentional orienting—age-related greater difficulties with disengaging attention from the RVF for the purpose of re-orienting attention to the LVF. The findings from the study presented in Chapter 3 build on Guilbert et al.'s findings by demonstrating that healthy ageing also relates to difficulties with the non-directional component of attentional orienting—age-related greater difficulties with disengaging attention from local-level information for the purpose of re-orienting attention to global-

level information. Together with the findings from Guilbert et al., the present findings extend our understanding of the right-hemisphere ageing hypothesis by suggesting that the RH-ageing process results in greater difficulties for both the directional and non-directional components of visual attention.

The second implication from Chapter 3 relates to the clinical relevance of these findings for neuropsychological research, particularly in patients with unilateral neglect. Previous studies (Morrow & Ratcliff, 1988; Posner et al., 1984; Posner et al., 1987; also see Aimola Davies, 2004; Bartolomeo & Sylvie, 2002; Loiser & Klein, 2001 for reviews) have suggested that patients with unilateral right-hemisphere damage demonstrate greater difficulties in disengaging attention from the right visual field and re-orienting attention to the left visual field, a pattern similar to that reported in healthy older adults by Guilbert et al. (2019). Future research is warranted to investigate whether patients with unilateral right-hemisphere damage also demonstrate difficulties in attentional orienting for global-local processing. Such research would contribute to our understanding of the role of the right and left hemisphere in the directional and non-directional components of visual attention, and inform the development of new neuropsychological assessment methods for attentional deficits in clinical populations.

6.1.3 Summary: Age-Related Changes in Global-Local Processing

Together, the findings from Chapters 2, 4, and 5 (discussed in Section 6.1.1) and Chapter 3 (discussed in Section 6.1.2) provide a more comprehensive understanding of the influence of healthy ageing on global-local processing. There are three key findings: First, older adults preferentially allocate attention to local-level information rather than global-level information, with processing efficiency for local information that is comparable to that of young adults. Second, when the task demands require that attention is directed to global-level information, older adults demonstrate greater difficulty with disengaging attention from local-level information, as compared to young adults. Third, once attention is directed to global-level information, older adults demonstrate reduced efficiency in processing the global information, compared to young adults (see Chen et al., 2024).

6.2 Hemispheric Asymmetry for Global-Local Processing Remains Intact with Age

Across all four empirical studies presented in this thesis, hemispheric asymmetry for global-local processing was examined using a hierarchical-figures paradigm with a divided visual field design, in which hierarchical figures were presented unilaterally to the left visual field (LVF) or to the right visual field (RVF). The logic behind the divided visual field design was that hierarchical figures briefly presented unilaterally to the LVF would be processed first by the right hemisphere (RH), and hierarchical figures briefly presented unilaterally to the RVF would be processed first by the left hemisphere (LH) (Beaumont, 1982; Bourne, 2006). The findings in this thesis indicate strong evidence that hemispheric asymmetry for global-local processing remains intact with age. Specifically, both young participants and older participants demonstrated: (1) better performance for detecting global stimuli presented in the LVF/RH compared to the RVF/LH, indicating right hemisphere specialisation for global processing (RH-global specialisation); and/or (2) better performance for detecting local stimuli presented in the RVF/LH compared to the LVF/RH, indicating left hemisphere specialisation for local processing (LH-local specialisation).

To the best of my knowledge, Oken et al. (1999) was the only study that adopted a divided visual field design to investigate hemispheric asymmetry for global-local processing in both young and older adults. They adopted a focused-attention task with a Go/No-go response mode. Our findings from the empirical studies that adopted a divided-attention task with a Go/No-go response mode (Chapters 2, 4, and 5) were consistent with those of Oken et al., indicating evidence that both young adults and older adults demonstrate RH-global specialisation and LH-local specialisation. There was one exception in Chapter 2. When testing with nonverbalisable shapes (as opposed to testing with letters and verbalisable objects), both age groups demonstrated LH-local specialisation in the absence of RH-global specialisation. See Table 6.2 for a summary of the findings for hemispheric asymmetry for global-local processing in Chapters 2, 3, 4, and 5 of this thesis and for Oken et al. (1999). In the following section (Section 6.3), I

discuss the extent to which the present findings regarding hemispheric asymmetry for global-local processing support the right-hemisphere ageing hypothesis.

Table 6.2

Summary of Findings Regarding Hemispheric Asymmetry for Global-Local Processing for Young and Older Participants

Chapter	Young *n*	Older *n*	Stimulus category	Attention task	Response mode	RH-global specialisation		LH-local specialisation	
						Young	Older	Young	Older
	27	34	Letter	Divided	Go/No-go	+	+	+	+
Chapter 2	27	32	VO	Divided	Go/No-go	+	+	+	+
	27	30	NVS	Divided	Go/No-go	–	–	+	+
Chapter 3	39	38	VO	Focused	Yes/No	+	+	–	–
Chapter 4	127	58	Letter	Divided	Go/No-go	+	+	+	+
Chapter 5	87	58	Letter	Divided	Go/No-go	+	+	+	+
Oken et al. (1999)	20	25	VO	Focused	Go/No-go	+	+	+	+

Note. VO = verbalisable object, NVS = nonverbalisable shape; RH-global specialisation = right hemisphere specialisation for global processing, LH-local specialisation = left hemisphere specialisation for local processing; Divided = divided-attention task, where participants were instructed to attend to the global level and local level concurrently, Focused = focused-attention task, where participants were instructed to attend to one processing level at a time, either to the global level or to the local level; Go/No-go = a Go/No-go response mode, where participants were instructed to respond when a target appears, and not to respond when no target appears, Yes/No = Yes/No response mode, where participants were instructed to make a 'Yes' response when a target appears, and to make a 'No' response when no target appears; + = significant findings found for right-hemisphere or left-hemisphere specialisation, – = no significant findings found for right-hemisphere or left-hemisphere specialisation.

6.3 Evidence for the Right-Hemisphere Ageing Hypothesis is Mixed

Earlier in the General Discussion, I discussed two key findings in this thesis regarding age-related changes in global-local processing (Section 6.1) and age-related changes in hemispheric asymmetry for global-local processing (Section 6.2). In this section, I will integrate these findings to discuss the extent to which they support the right-hemisphere ageing hypothesis.

The right-hemisphere ageing hypothesis proposes that the RH is more vulnerable to ageing than the LH, with LH functions remaining relatively stable across the lifespan (Klisz, 1978). In the General Introduction (Section 1.3.2), I reviewed three types of behavioural study that have investigated the right-hemisphere ageing hypothesis:

1. The first type of behavioural study examined whether young adults and older adults differ in overall performance in the LVF compared to the RVF;
2. The second type of behavioural study examined whether young adults and older adults differ in overall performance on tasks assumed to be primarily processed by the RH compared to those assumed to be primarily processed by the LH;
3. The third type of behavioural study examined whether young adults and older adults differ in hemispheric asymmetry for RH-associated tasks compared to hemispheric asymmetry for LH-associated tasks.

This thesis examined hemispheric asymmetry for global-local processing in young participants and older participants using a divided visual field design, in which hierarchical figures were presented unilaterally to the LVF or to the RVF. This design enables a systematic investigation of the right-hemisphere ageing hypothesis in relation to the three types of behavioural study outlined above. Specifically, the findings in this thesis address whether young adults and older adults differ in:

1. Overall performance in the LVF compared to the RVF;
2. Overall performance on global processing compared to local processing;
3. RH specialisation for global processing compared to LH specialisation for local processing.

In the following subsections, I discuss whether the present findings for each of the three aspects outlined above provide support for the right-hemisphere ageing hypothesis.

6.3.1 No Evidence for Age-Group Differences in Overall Performance in the Left Visual Field Compared to the Right Visual Field

As reviewed in the General Introduction (Section 1.3.2), the first type of behavioural study investigated the right-hemisphere ageing hypothesis by examining age-related changes in overall performance in the LVF (or the left side of an object) compared to the RVF (or the right side of an object) (e.g., Guilbert et al., 2019; Schmitz & Peigneux, 2011). The logic is that performance in the LVF reflects RH processing efficiency, as stimulus presented in the LVF would be processed first by the RH; and that performance in the RVF reflects LH processing efficiency, as stimulus presented in the RVF would be processed first by the LH. Therefore, evidence supporting the right-hemisphere ageing hypothesis would mean that older adults would demonstrate worse overall performance in the LVF/RH compared to the RVF/LH.

The findings in this thesis indicate there is evidence of no age-group differences in overall performance in the LVF/RH compared to the RVF/LH. Specifically, in Chapters 2, 4, and 5, where a divided-attention task with a Go/No-go response mode was adopted, neither young participants nor older participants demonstrated overall performance differences when the hierarchical figures were presented in the LVF compared to in the RVF. This was evident regardless of whether the participants were detecting a target at the global level or at the local level. These findings indicate that older participants demonstrated comparable overall performance in the LVF/RH and the RVF/LH, which is not in line with the first type of behavioural study that reported evidence supporting the right-hemisphere ageing hypothesis.

The one exception was in Chapter 3, where a focused-attention task with a Yes/No response mode was adopted. Specifically, older participants demonstrated better performance when the hierarchical figures were presented in the RVF/LH compared to the LVF/RH. In contrast, young participants did not demonstrate performance differences between the two visual fields. These findings for older participants are

unexpected and in contrast with the right-hemisphere ageing hypothesis, where older adults are predicted to demonstrate worse overall performance in the LVF/RH compared to the RVF/LH. One possible explanation of these unexpected findings relates to task difficulty. In Chapter 3, the focused-attention task with a Yes/No detection-response mode involved high task demands, requiring participants to: (1) allocate attention across the two visual fields; (2) coordinate between the two opposing response options (i.e., 'Yes' *versus* 'No'); and (3) actively re-orient attention back to the task-relevant level when a target appeared at the task-irrelevant level. Older participants experiencing task difficulty may have strategically prioritised attention to one visual field while compromising performance in the other visual field. However, future research is needed to clarify why the LVF may have been prioritised in older participants and to determine whether the observed better performance in the LVF/RH for older adults can be replicated.

6.3.2 Strong Evidence for an Age-Related Worse Performance on Global Processing Compared to Local Processing

As reviewed in the General Introduction (Section 1.3.2), the second type of behavioural study investigated the right-hemisphere ageing hypothesis by examining age-related changes in overall performance on tasks assumed to be primarily processed by the RH compared to those assumed to be primarily processed by the LH (e.g., Jenkins et al., 2000; Wang et al., 2019). Therefore, evidence supporting the right-hemisphere ageing hypothesis would mean that older adults would demonstrate worse overall performance on the RH-associated tasks compared to the LH-associated tasks, regardless of the visual field of presentation.

The findings in Chapters 2, 4, and 5 (discussed in Section 6.1.1) indicate there is strong evidence that older adults demonstrate worse performance for global processing (i.e., primarily processed by the RH) compared to young adults, whereas performance for local processing (i.e., primarily processed by the LH) remains intact with age. This was evident regardless of whether the hierarchical figures were presented in the LVF or in the RVF. These findings are in line with the second type of behavioural study that has provided support for the right-hemisphere ageing hypothesis.

Notably, the findings in Chapter 3 (discussed in Section 6.1.2) indicate there is evidence that older adults demonstrate greater age-related difficulties in disengaging attention from the local level and re-orienting attention to the global level, as compared to disengaging attention from the global level and re-orienting attention to the local level. These findings extend what was previously known about the right-hemisphere ageing hypothesis, suggesting that right-hemisphere ageing involves not only reduced efficiency in global processing but also a difficulty in attentional orienting for global-local processing—greater difficulties with disengaging attention from local-level information for the purpose of re-orienting attention to global-level information, with global-level processing considered a RH function.

6.3.3 No Evidence for Age-Group Differences in Right Hemisphere Specialisation for Global Processing Compared to Left Hemisphere Specialisation for Local Processing

As reviewed in the General Introduction (Section 1.3.2), the third type of behavioural study investigated the right-hemisphere ageing hypothesis by examining age-related changes in hemispheric asymmetry for RH-associated tasks compared to hemispheric asymmetry for LH-associated tasks (e.g., Beaton et al., 2012; Hausmann et al., 2003; Oken et al., 1999; Prodan et al., 2007). Therefore, evidence supporting the right-hemisphere ageing hypothesis would mean that older adults would demonstrate reduced hemispheric asymmetry for RH-associated tasks compared to hemispheric asymmetry for LH-associated tasks. The findings in Chapters 2, 4, and 5 (discussed in Section 6.2) indicate there is consistent evidence that there are no age-group differences in RH specialisation for global processing and LH specialisation for local processing. Specifically, when a divided-attention task with a Go/No-go response mode was adopted, both young participants and older participants demonstrated better performance for detecting global stimuli presented in the LVF/RH compared to the RVF/LH; and (2) better performance for detecting local stimuli presented in the RVF/LH compared to the LVF/RH. These findings indicate that, in older participants, global information was not processed by both hemispheres but instead was processed predominantly by the RH. These findings are not in line with the third type of behavioural

study that reported evidence supporting the right-hemisphere ageing hypothesis. See Table 6.3 for a summary of the findings regarding the right-hemisphere ageing hypothesis.

Table 6.3

Summary of Findings for the Right-Hemisphere Ageing Hypothesis

Age-related differences in	Chapter 2	Chapter 3	Chapter 4	Chapter 5
1. Overall performance in the LVF compared to the RVF	–	Opposing	–	–
2. Overall performance on global processing compared to local processing	+	+	+	+
3. RH specialisation for global processing compared to LH specialisation for local processing	–	–	–	–

Note. LVF = left visual field, RVF = right visual field; RH = right hemisphere, LH = left hemisphere; + = significant findings supporting the right-hemisphere ageing hypothesis, – = no significant finding supporting the right-hemisphere ageing hypothesis; Opposing = significant findings opposing the right-hemisphere ageing hypothesis.

6.3.4 Summary: Mixed Evidence for the Right-Hemisphere Ageing Hypothesis

To summarise, this thesis demonstrates mixed evidence for the right-hemisphere ageing hypothesis. Specifically, the findings suggest that although older participants did demonstrate an age-related worse performance for global processing, the RH of older participants was still more efficient compared to the LH for processing the global information.

6.4 Individual Differences in Behavioural Measures for Global-Local Processing

Research on global-local processing has primarily focused on understanding hemispheric asymmetry for global-local processing at the group level (e.g., Oken et al., 1999; Peterson & Peterson, 2014; Yovel et al., 2001), or on understanding whether different groups of participants demonstrate differences in their relative bias for global processing and local processing (e.g., Lux et al., 2008; McKone et al., 2010). In contrast, individual differences in these research questions have been relatively underexplored. Investigating these individual differences could provide important insights into the reliability and validity of the behavioural paradigm commonly used to measure global-local processing. This thesis addresses these research gaps and indicates two key findings regarding individual differences:

1. There are individual differences within a behavioural divided visual field design measuring hemispheric asymmetry for global-local processing;
2. There are individual differences across behavioural measures of global-local processing bias.

6.4.1 Individual Differences in a Behavioural Divided Visual Field Design Measuring Hemispheric Asymmetry for Global-Local Processing

The empirical studies presented in Chapter 4 investigated individual differences in hemispheric asymmetry for global-local processing using a behavioural divided visual field design. Although individuals demonstrate differences in functional hemispheric asymmetry, many of these individual differences have been treated as random errors and largely ignored (Hellige, 1993). While behavioural studies have provided support for the proposal that, at the group level, there is RH-global specialisation and LH-local specialisation (e.g., Brederoo et al., 2017; Chen et al., 2024; Yovel et al., 2001), there have been limited behavioural and neuroimaging investigations of individual differences in hemispheric asymmetry for global-local processing.

In Chapter 4, a total of 127 young participants and 58 older participants completed a hierarchical-figures task using a divided-attention task with a Go/No-go response

mode. The group-level findings indicate that both young participants and older participants demonstrated faster performance for global targets presented in the LVF/RH compared to the RVF/LH, providing evidence for RH-global specialisation at the group level. Both age groups also demonstrated faster performance for local targets presented in the RVF/LH compared to the LVF/RH, providing evidence for LH-local specialisation at the group level. However, the individual-level findings indicate that, although the majority of participants demonstrated RH-global specialisation alongside LH-local specialisation, the expected pattern of hemispheric asymmetry was observed in only marginally more than 50% of the participants across the two age groups (59.84% in young participants, 51.72% in older participants). Importantly, our findings identified distinctive subgroups when examining hemispheric asymmetry for global-local processing using a divided visual field design. Specifically, participants in these subgroups demonstrated an overall better performance in one visual field compared to the other visual field, and this better performance in one visual field was evident for both global processing and local processing.

There are three interpretations of the subgroups observed from a behavioural divided visual field design. The first interpretation is that these subgroups may demonstrate hemispheric involvement in global-local processing that does not match the expected patterns of RH-global specialisation and LH-local specialisation. Specifically, these subgroups may have greater involvement of one hemisphere compared to the other hemisphere when processing global and local information, leading to either an overall RH advantage or an overall LH advantage for global-local processing. The second interpretation is that these subgroups may have strategically prioritised attention to one visual field while compromising performance in the other visual field due to the difficulty of the task design. The third interpretation is that the existence of these hemispheric asymmetry subgroups observed may partly reflect the measurement noise found with the behavioural divided visual field design. This is particularly relevant given that previous studies examining tasks measuring hemispheric specialisation for language processing have reported that language lateralisation, as studied with the behavioural divided visual field design, demonstrated low test-retest reliability (e.g., Parker et al., 2021; Parker et al., 2022; Voyer, 1998) and inconsistent

correlations between behavioural measures and neuroimaging measures of language lateralisation (e.g., Parker et al., 2022; Krach et al., 2006; also see Hunter & Brysbaert, 2008; Van der Haegen et al., 2011).

These findings open new research avenues for investigating individual differences in hemispheric asymmetry for global-local processing. Future research is warranted to examine the test-retest reliability of these hemispheric asymmetry subgroups identified in the present study, to determine whether they reflect stable individual differences in hemispheric asymmetry for global-local processing. In addition, neuroimaging methods should also be incorporated to examine whether these hemispheric asymmetry subgroups demonstrate lateralised neural activation patterns that are consistent with their behavioural performance.

6.4.2 Individual Differences Across Behavioural Measures for Global-Local Processing Bias

The empirical studies presented in Chapter 5 investigated individual differences in the relationship between two behavioural measures of the global-local processing bias. The Ebbinghaus illusion task represents another common experiment paradigm, in addition to Navon's (1977) hierarchical-figures task, used to measure group-level differences in the relative bias for global processing and local processing (i.e., the global-local processing bias). The rationale behind the Ebbinghaus illusion task is that the tendency to attend locally rather than globally (i.e., a local-processing bias) is thought to reduce susceptibility to the Ebbinghaus illusion. Therefore, group-level differences in susceptibility to the Ebbinghaus illusion have been interpreted as reflecting underlying differences in the global-local processing bias between different groups of participants (e.g., Davidoff et al., 2008; de Fockert et al., 2007; Doherty et al., 2008; Doherty et al., 2010; Phillips et al., 2004). However, no prior study has directly investigated whether the relationship between the global-local processing bias and susceptibility to the Ebbinghaus illusion would be evident at the individual level. That is, whether individuals with a stronger local-processing bias are less susceptible to the Ebbinghaus illusion, as compared with individuals with a stronger global-processing bias.

In Chapter 5, a total of 87 young participants and 58 older participants completed both a hierarchical-figures task and an Ebbinghaus illusion task. There were inconsistent findings between the two tasks at both the group level and at the individual level. At the group level, findings from the hierarchical-figures task confirmed that older participants demonstrated a local-processing bias compared to young adults, whereas findings from the Ebbinghaus illusion task indicated that the two age groups did not differ in susceptibility to the Ebbinghaus illusion. At the individual level, it was the young and older individuals with the stronger local-processing bias on the hierarchical-figures task who were *more* susceptible to the Ebbinghaus illusion. These findings contradict what has been proposed to be the rationale behind the Ebbinghaus illusion task, which predicts that individuals with a stronger local-processing bias would be less susceptible to the Ebbinghaus illusion. The group-level and individual-level findings suggest that the Ebbinghaus illusion task alone may not be a reliable or valid measure for the global-local processing bias at either the group level or at the individual level. More broadly, different experiment paradigms that are assumed to measure the same construct of global-local processing bias may not yield consistent results. Future research is therefore warranted, with the goal of employing multiple experiment paradigms to replicate the age-related changes in global-local processing bias reported in this thesis (see Lacko et al., 2023 for a systematic investigation into the validity and reliability of six widely used global-local tasks).

6.5 Future Directions

In Section 6.3, I provided a summary for the finding that there is mixed evidence for the right-hemisphere ageing hypothesis. Specifically, although older participants did demonstrate age-related worse performance for global processing, the RH of older participants was still more efficient compared to the LH at processing the global information. These findings suggest that the age-related worse performance for global processing could not be explained by a reduction in RH functional specialisation for global processing. A further question then arises: *What other neurocognitive mechanisms might account for the observed age-related worse performance in global processing in older adults?*

Here, I propose a possible account of the right-hemisphere ageing hypothesis—healthy ageing may involve changes in the RH that are involved with enhanced attentional responsiveness to incoming visual information. Visual attention involves a dynamic of both activation and inhibition between the RH and the LH. The hemisphere specialised for the incoming stimuli needs to enhance attentional responsiveness, whereas the non-specialised hemisphere needs to inhibit (or suppress) interference from the specialised hemisphere. For example, when processing global information, the RH needs to enhance attentional responsiveness, while the LH needs to inhibit the processing of the global information. Whereas, when processing local information, the LH needs to enhance attentional responsiveness, while the RH needs to inhibit the processing of the local information. One possibility is that healthy ageing influences the extent to which the RH can enhance attentional responsiveness to global information, while the attentional responsiveness of the LH to local information remains intact with age.

How might this activation *versus* inhibition account be examined? Alpha oscillations in electroencephalogram (EEG) recordings are a well-established electrophysiological marker of visual attention, particularly in relation to inhibitory processes. The brain is constantly active, producing ongoing fluctuations in postsynaptic potentials across billions of neurons, which together generate the scalp-recorded EEG. Within these neural activities, event-related potential components reflect brief, time-locked responses to specific events, whereas neural oscillations reflect rhythmic, ongoing activity that is not tied to specific events and instead arise from feedback loops in the brain (Luck, 2014). Among these neural oscillations, alpha oscillations, fluctuating at approximately 7 to 13 Hz, have been associated with inhibitory processes in visual attention (Clayton et al., 2018; Klimesch et al., 2007). The idea is that a decrease in alpha amplitude reflects enhanced attentional responsiveness to incoming visual stimuli, whereas an increase in alpha amplitude reflects increased inhibition in the processing of incoming visual stimuli. For example, changes in alpha amplitude have been observed during attentional orienting in the LVF and RVF (Gould et al., 2011; Samaha et al., 2016). Directing attention to the LVF was associated with a decrease in alpha amplitude over the contralateral RH and an increase in alpha amplitude over the ipsilateral LH; whereas directing attention to the RVF was associated with a decrease in alpha amplitude over the

contralateral LH and an increase in alpha amplitude over the ipsilateral RH. These findings suggest that directing attention to one visual field involves enhanced attentional responsiveness in the contralateral hemisphere with increased inhibition in the ipsilateral hemisphere.

To the best of my knowledge, only two studies (e.g., Romei et al., 2012; Volberg et al., 2009) have examined the relationship between alpha oscillations and global-local processing in young adults. Both studies provided consistent evidence that alpha activity reflects the dynamic of activation and inhibition between the RH and LH during global-local processing. In the study by Volberg et al., a hierarchical figure was presented centrally on each trial, and it was preceded by an auditory cue instructing participants to detect either the global stimulus or the local stimulus. Behavioural performance on individual trials was categorised into three conditions according to speed of responding: fast, intermediate, and slow. Alpha amplitude was measured from the post-cue and pre-stimulus interval. The results indicated that fast reaction time to global stimuli was associated with a decrease in alpha amplitude over the RH and an increase in alpha amplitude over the LH. Whereas slow reaction time to global stimuli was associated with an increase in alpha amplitude over the contralateral RH. These findings suggest that better behavioural performance in detecting global stimuli is associated with a decrease in alpha amplitude over the RH, indicating enhanced attentional responsiveness in the RH for global processing. Likewise, fast reaction time to local stimuli was associated with a decrease in alpha amplitude over the contralateral LH and an increase in alpha amplitude over the ipsilateral RH. Whereas slow reaction time to local stimuli was associated with an increase in alpha amplitude over the contralateral LH. These findings suggest that the better behavioural performance in detecting local stimuli is associated with a decrease in alpha amplitude over the LH, indicating enhanced attentional responsiveness in the LH for local processing.

Building on the findings of Volberg et al. (2009), Romei et al. (2012) examined the causal relationship between alpha oscillations and global-local processing in young adults using rhythmic transcranial magnetic stimulation (TMS). This brain stimulation method delivers brief magnetic pulses over cortical sites, inducing transient modulation

of neural activity in the targeted sites. In the study by Romei et al., rhythmic TMS at 10 Hz, corresponding to the alpha oscillation frequency, was applied either over the right posterior parietal sites or over the left posterior parietal sites before the presentation of each hierarchical figure (i.e., per trial). The results indicated that 10 Hz stimulation over the right parietal sites resulted in worse behavioural performance for global processing, whereas 10 Hz stimulation over the left parietal sites resulted in worse behavioural performance for local processing. Together, the findings of Volberg et al. (2009) and Romei et al. (2012) indicate that alpha oscillations in young adults modulate hemispheric asymmetry in global-local processing. Behavioural performance for global processing is associated with decreased alpha activity over the RH and increased alpha activity over the LH. Behavioural performance for local processing is associated with decreased alpha activity over the LH and increased alpha activity over the RH.

As an extension from these findings in young adults, it is plausible that the age-related worse performance in global processing observed for the older participants in this thesis may reflect age-related changes in alpha activity over the RH in older adults. Specifically, older adults may demonstrate less reduction in alpha amplitude over the RH during global processing compared to young adults, indicating an age-related difficulty with enhance attentional responsiveness of the RH for global processing. To the best of my knowledge, no study has investigated age-related changes in alpha oscillations during global-local processing in young and older adults. Filling this research gap would allow for a direct examination of this possible account of the right-hemisphere ageing hypothesis and provide new insights into how electrophysiological markers of inhibitory processes relate to age-related changes in hemispheric asymmetry. [1]

[1] In light of this research gap, I have collected EEG recordings from 70 young participants. Data collection for the older participant group is still ongoing. In this EEG study, participants completed the same hierarchical-figures task as adopted in Chapter 2, in which a hierarchical figure was presented unilaterally to the LVF or to the RVF within a divided visual field design. The EEG data are not reported in the present thesis, as the scope of the current thesis focuses on behavioural evidence for hemispheric asymmetry for global-local processing.

6.6 Conclusion

This thesis contributes to the understanding of how healthy ageing influences the 'double brain' in navigating complex visual structures. There are four key findings. First, healthy ageing influences not only the ability to process global information but also the ability to disengage attention from local-level information and re-orient attention to global-level information. Second, hemispheric asymmetry for global-local processing remains intact with age: in both young adults and older adults, the right hemisphere is more efficient in processing global information (compared to the left hemisphere), and the left hemisphere is more efficient in processing local information (compared to the right hemisphere). Third, evidence for the right-hemisphere ageing hypothesis is mixed, indicating that the mechanisms underlying the age-related difficulties for global processing observed in older adults are not yet fully understood. Fourth, there are individual differences in behavioural measures for global-local processing. Together, the findings in this thesis provide new theoretical implications and future research directions for understanding the influence of healthy ageing on functional hemispheric asymmetry and its impact on visual attention across the life span.

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Appendix A Supplementary Analyses for Chapter 3

A.1 Analysis 1. Reaction Time Data for 'Yes' Responses to the Congruent-Target Figures

A.1.1 Statistical Analysis Plan

The reaction time (RT) data for 'Yes' responses to the congruent-target figures (for the 39 young participants and 38 older participants included in the statistical analyses of the main study) were analysed. Prior to statistical analyses of the congruent-target figures, RT for the correct trials were screened in two steps. First, trials faster than 250 ms were excluded. No trials for young participants or older participants were excluded. Next, trials slower than 2.5 SD from the mean were winsorised for each of the repeated-measures conditions for each participant: for young participants, 1.43% of trials were winsorised, and for older participants, 1.67% of trials were winsorised. The repeated-measure conditions were: (1) 'Yes' responses in the global-focused condition to congruent-target figures presented in the LVF and in the RVF; (2) 'Yes' responses in the local-focused condition to congruent-target figures presented in the LVF and in the RVF. The setup of the statistical analyses was the same as the linear mixed-effects regression conducted for the 'Yes' response condition reported in the main study.

A.1.2 Results

The omnibus analyses and additional analyses are reported in full in Table A.1. Results for the interaction effects pertaining to Research Question 2 are in the following sections.

A.1.2.1 Statistical Analyses for Research Question 2: Right-Left Hemispheric Asymmetry for Global-Local Processing in Congruent-Target Figures. The omnibus analysis for the congruent-target figures (see Panel 1, Table A.1) indicated there was a significant three-way interaction with Age Group: Focus Level (global-focused, local-

focused) × Visual Field (LVF, RVF) × Age Group (young, older). As planned, additional analyses of the congruent-target figures for each of the two age groups (young, older) were conducted (see Panels 2 and 3, Table A.1). A significant main effect of Visual Field was found for both young and older participants. Additionally, a significant Focus Level × Target Type interaction was found for older participants, but not for young participants.

For young participants, the significant main effect of Visual Field indicated that young participants demonstrated faster 'Yes' responses to congruent-target figures presented in the LVF/RH ($M_{LVF/RH}$ = 523.46 ms, 95% CI [499.65, 547.28]) compared to the RVF/LH ($M_{RVF/LH}$ = 533.29 ms, 95% CI [509.48, 557.11]).

For older participants, results for the post hoc pairwise comparisons for the Focus Level × Visual Field interaction were as follows:

1. The 'Yes' responses in the global-focused condition to congruent-target figures were faster in the LVF/RH compared to the RVF/LH, MD = –78.08 ms, 95% [–99.82, –56.34], SE = 8.46, t = –9.23, p < .001, d = 0.54;
2. The 'Yes' responses in the local-focused condition to congruent-target figures were faster in the LVF/RH compared to the RVF/LH, MD = –35.55 ms, 95% [–57.15, –13.94], SE = 8.40, t = –4.23, p < .001, d = 0.13;
3. The 'Yes' responses to congruent-target figures in the RVF/LH were faster for the local-focused condition compared to the global-focused condition, MD = –47.60 ms, 95% [–83.15, –12.06], SE = 13.44, t = 3.54, p = .004, d = 0.52;
4. The 'Yes' responses to congruent-target figures in the LVF/RH were not significantly different for the global-focused condition compared to the local-focused condition, MD = –5.07 ms, 95% [–30.39, 40.52], SE = 13.40, t = 0.38, p = .98, d = 0.04. See Figure A.1 for estimated marginal means

Table A.1

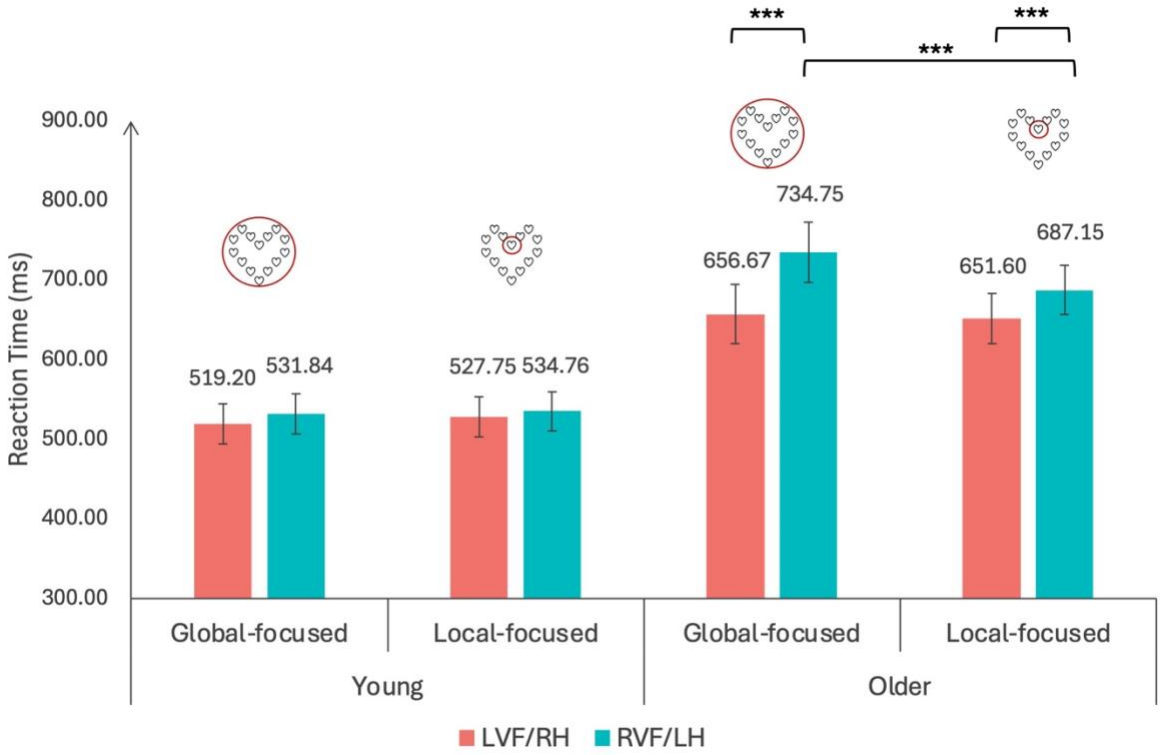
Omnibus and Additional Analyses: Reaction Times for 'Yes' Responses to Congruent-Target Figures

Effects	df_1	df_2	F	p	η^2
1. Omnibus analysis					
Focus Level	1	77.53	2.36	.13	.03
Visual Field	1	73.80	71.07	< .001***	.49
Age Group	1	74.96	62.64	< .001***	.46
Focus Level × Visual Field	1	4554.36	11.24	< .001***	.003
Focus Level × Age Group	1	74.53	5.72	.02*	.07
Visual Field × Age Group	1	73.80	35.36	< .001***	.32
Focus Level × Visual Field × Age Group	1	4554.36	6.62	.01*	.002
2. Additional analysis for young participants					
Focus Level	1	37.70	0.84	.36	.02
Visual Field	1	2368.32	5.78	.02*	.002
Focus Level × Visual Field	1	2368.37	0.47	.49	.0002
3. Additional analysis for older participants					
Focus Level	1	36.93	4.80	.03*	.003
Visual Field	1	2257.27	90.86	< .001***	.04
Focus Level × Visual Field	1	2256.79	12.73	< .001***	.006

Note. * $p < .05$, *** $p < .001$.

Figure A.1

Right-Left Hemispheric Asymmetry for Global-Local Processing: Estimated Marginal Means for Focus Level by Visual Field Interaction—'Yes' Responses to Congruent-Target Figures



Note. *** $p < .001$. Error bars represent 95% confidence intervals. LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere.

Example hierarchical figures illustrate 'Yes' responses, with the target ♡ (heart) presented at both the task-relevant level and the task-irrelevant level. Large red circles illustrate the global-focused condition, where participants were instructed to focus on the global level of the hierarchical figure. Small red circles illustrate the local-focused condition, where participants were instructed to focus on the local level of the hierarchical figure.

A.2 Analysis 2. Accuracy Data for 'Yes' and 'No' Responses

A.2.1 Statistical Analysis Plan

The accuracy data (for the 39 young participants and 38 older participants included in the statistical analyses of the main study) were analysed to ensure there was no speed-accuracy trade-off. Logistic mixed-effects regression was adopted, in which accuracy data by trials (i.e., correct, incorrect) for each participant were entered as the dependent variable. Similar to the statistical analyses for RT, two omnibus analyses were conducted for accuracy: one omnibus analysis for the 'Yes' responses and one omnibus analysis for the 'No' responses. The setup for the fixed effects, random intercepts, and random slopes in the two omnibus analyses for accuracy was the same as the RT analyses reported in the main study.

The statistical analyses for accuracy were carried out in R (version 2024.09.1+394), and all the fixed effects were deviation coded. The logistic mixed-effects regressions were conducted using the "glmer" function in the "lme4" package. The Type-III analyses of variance (ANOVA) tables with Wald chi-squares tests were obtained using the "Anova" function in the "car" package. Post hoc pairwise comparisons with Tukey-corrected *p* values were conducted using the "emmeans" function in the "emmeans" package. Estimated marginal means and confidence intervals were obtained using the "effect" function in the "effects" package. Post hoc pairwise comparisons reported the mean difference (MD) in the log odds ratio scale.

A.2.2 Results

The omnibus analyses are reported in full in Table A.2. Results for the interaction effects pertaining to the two research questions are presented in the following sections.

A.2.2.1 Statistical Analyses of Accuracy for Research Question 1: Age-Related Differences in Attentional Orienting for Global-Local Processing. The omnibus analysis for the 'No' responses (see Panel 2, Table A.2) indicated that there was no

significant Focus Level × Target Type interaction or Focus Level × Target Type × Age Group interaction. See Figure A.2 for the estimated marginal means of accuracy.

A.2.2.2 Statistical Analyses of Accuracy for Research Question 2: Right-Left Hemispheric Asymmetry for Global-Local Processing.

'Yes' Responses. The omnibus analysis for the 'Yes' responses (see Panel 1, Table A.2) indicated there was a significant two-way interaction with Visual Field: Visual Field (LVF, RVF) × Age Group (young, older). The two-way interaction of Focus Level × Visual Field and the three-way interaction of Focus Level × Visual Field × Age Group were not significant. See Figure A.3 for the estimated marginal means of accuracy.

Results for the post hoc pairwise comparisons for the Visual Field × Age Group interaction were as follows:

1. young participants' 'Yes' responses to LVF/RH stimuli ($M_{\text{young-LVF/RH}}$ = 96.31%, 95% CI [94.74%, 97.42%]) were not significantly different from their 'Yes' responses to RVF/LH stimuli ($M_{\text{young-RVF/LH}}$ = 95.96%, 95% CI [94.28%, 97.15%]), MD = 0.10, 95% [–0.36, 0.55], SE = 0.18, z = 0.52, p = .95;
2. older participants' 'Yes' responses to LVF/RH stimuli ($M_{\text{older-LVF/RH}}$ = 88.46%, 95% CI [85.01%, 91.20%]) were more accurate than their responses to the RVF/LH stimuli ($M_{\text{older-RVF/LH}}$ = 80.38%, 95% CI [75.47%, 84.50%]), MD = 0.63, 95% [0.34, 0.92], SE = 0.11, z = 5.52, p < .001;
3. young participants' 'Yes' responses to LVF/RH stimuli were more accurate than older participants' 'Yes' responses to LVF/RH stimuli, MD = –1.13, 95% [–1.84, –0.61], SE = 0.24, z = –5.12, p < .001;
4. young participants' 'Yes' responses to RVF/LH stimuli were more accurate than older participants' 'Yes' responses to RVF/LH stimuli, MD = –1.76, 95% [–2.35, –1.16], SE = 0.23, z = –7.57, p < .001.

'No' Responses. The omnibus analysis for the 'No' responses (see Panel 1, Table A.2) indicated there were no significant interactions with Visual Field. See Figure C for the estimated marginal means of accuracy.

Overall, there was no evidence of a speed-accuracy trade-off for either 'No' responses or 'Yes' responses. Slower RT across conditions for young participants and older participants was not accompanied by higher accuracy.

Table A.2

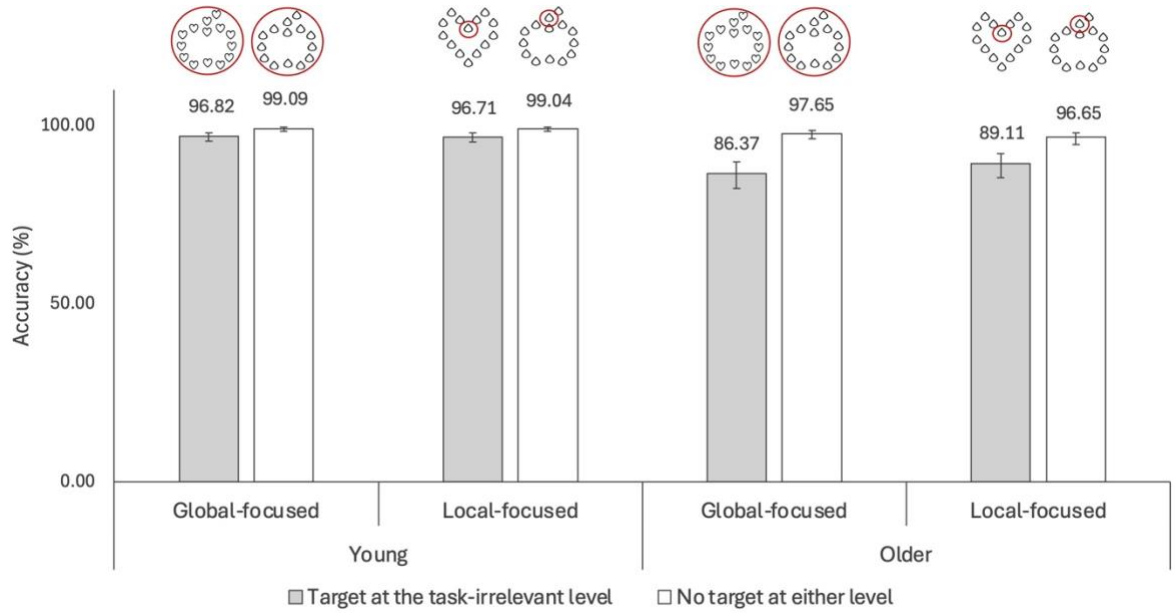
Omnibus Analyses: Accuracy for 'Yes' Responses and 'No' Responses

Effects	*df*	χ^2	*p*
1. Omnibus analysis for 'Yes' responses			
Focus Level	1	2.45	.12
Visual Field	1	11.71	< .001***
Age Group	1	50.00	< .001***
Focus Level × Visual Field	1	3.84	.05
Focus Level × Age Group	1	1.44	.23
Visual Field × Age Group	1	6.36	.01*
Focus Level × Visual Field × Age Group	1	0.12	.73
2. Omnibus analysis for 'No' responses			
Focus Level	1	0.09	.76
Visual Field	1	0.02	.88
Target Type	1	86.15	< .001***
Age Group	1	28.64	< .001***
Focus Level × Visual Field	1	0.87	.35
Focus Level × Target Type	1	2.34	.13
Focus Level × Age Group	1	0.0006	.98
Visual Field × Target Type	1	0.70	.40
Visual Field × Age Group	1	1.21	.27
Target Type × Age Group	1	1.45	.23
Focus Level × Visual Field × Target Type	1	2.43	.12
Focus Level × Visual Field × Age Group	1	0.32	.57
Focus Level × Target Type × Age Group	1	2.30	.13
Visual Field × Target Type × Age Group	1	2.56	.11
Focus Level × Visual Field × Target Type × Age Group	1	0.18	.67

Note. * $p < .05$; *** $p < .001$.

Figure A.2

Age-Related Differences in Attentional Orienting for Global-Local Processing: Estimated Marginal Means for Focus Level by Target Type Interaction—Accuracy for 'No' Responses

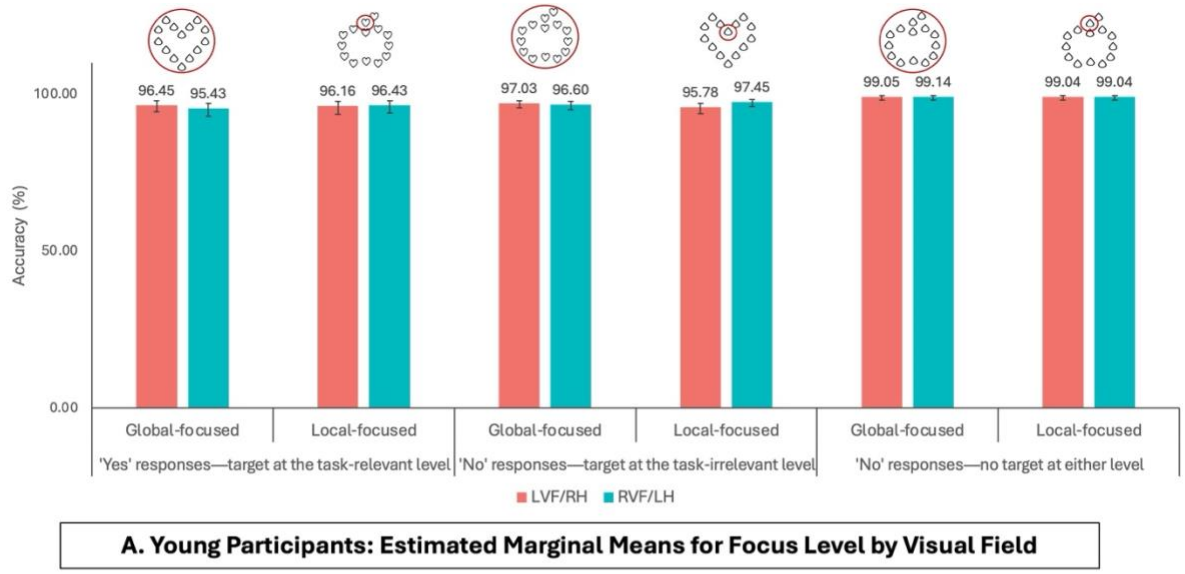


Note. Error bars represent 95% confidence intervals.

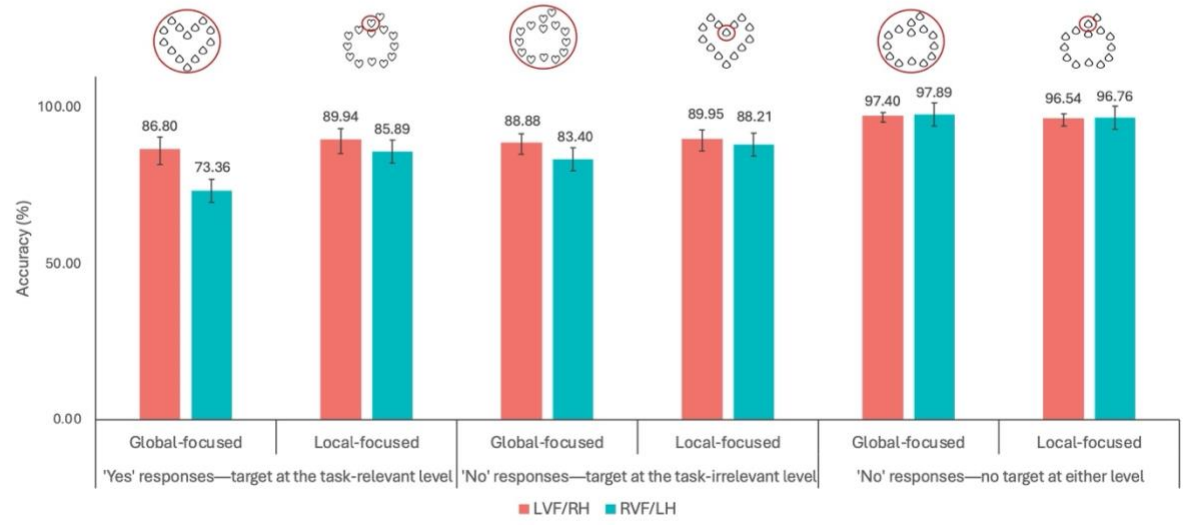
These example hierarchical figures illustrate the 'No' responses, in which the target ♡ (heart) was either presented at the task-irrelevant level (i.e., presented at the local level in the global-focused condition, or at the global level in the local-focused condition) or there was no target at either level (i.e., the distractors, either [apple] or [drop], were presented at both the task-relevant level and the task-irrelevant level). Large red circles illustrate the global-focused condition, where participants were instructed to focus on the global level of the hierarchical figure. Small red circles illustrate the local-focused condition, where participants were instructed to focus on the local level of the hierarchical figure. Grey bars illustrate the conditions in which the target ♡ was presented at the task-irrelevant level, and white bars illustrate the conditions in which no target was presented at either the task-relevant or task-irrelevant level.

Figure A.3

Right-Left Hemispheric Asymmetry for Global-Local Processing: Estimated Marginal Means for Focus Level by Visual Field Interaction—Accuracy for 'Yes' Responses and 'No' Responses



A. Young Participants: Estimated Marginal Means for Focus Level by Visual Field



B. Older Participants: Estimated Marginal Means for Focus Level by Visual Field

Note. LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere. Error bars represent 95% confidence intervals. Example hierarchical figures illustrate 'Yes' responses, with the target ♡ (heart) presented at the task-relevant level (i.e., presented at the global level in the global-focused condition, or at the local level in the local-focused condition). Example hierarchical figures illustrate 'No' responses, with either the target ♡ (heart) presented at the task-irrelevant level (i.e., local level in the global-focused condition, or global level in the local-focused condition) or no target presented at either level (i.e., distractors, either 🍎 [apple] or 💧 [drop], presented at the task-relevant level and at the task-irrelevant level). Large red circles illustrate the global-focused condition, where participants were instructed to focus on the global level of the hierarchical figure. Small red circles illustrate the local-focused condition, where participants were instructed to focus on the local level of the hierarchical figure.

Appendix B Supplementary Analyses for Chapter 4

B.1 Linear Mixed-Effects Models for Age-Group Differences in Hemispheric Asymmetry for Global-Local Processing

We conducted a linear mixed-effects model (equivalent to the omnibus ANOVA reported in the Results section of Chapter 4; see Section 4.3.3) to confirm that minor differences in the experiment design across the four experimenters did not influence the overall results. The independent variables included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF), and one between-subjects predictor: Age Group (young, older). The dependent variable was the reaction time (RT) of correct trials for each participant. The random intercepts included two cluster factors of Participants and Experimenters. The random slopes included one within-subjects factor of Level (global, local), as the within-subjects factor of Visual Field (LVF, RVF) was excluded from the random slopes to avoid over-fitting due to singular fits (i.e., the random slopes were too complex to be supported by the data).

The results of the linear mixed-effects model were consistent with the results of the omnibus ANOVA reported in the Results section of Chapter 4 (see Section 4.3.3). There were significant main effects for Level and Age Group, but there were no significant main effects for Visual Field. There were significant interactions for Level × Age Group and Level × Visual Field, but there was no significant Visual Field × Age Group interaction, nor was there a significant Level × Visual Field × Age Group interaction. See Table B.1 for the statistics.

We opted to report the results of the omnibus ANOVA because the effect sizes derived from the linear mixed-effects model are not directly comparable to the conventional effect size measures, such as η_p^2 and Cohen's *d*.

Table B.1

Linear Mixed-Effects Model for Age-Group Differences in Hemispheric Asymmetry for Global-Local Processing

Effects	df_1	df_2	F	p
Level	1	183.01	89.32	< .001***
Visual Field	1	366.00	0.19	.67
Age Group	1	178.57	26.12	< .001***
Level × Visual Field	1	366.00	101.76	< .001***
Level × Age Group	1	183.01	109.52	< .001***
Visual Field × Age Group	1	366.00	0.35	.55
Level × Visual Field × Age Group	1	366.00	0.23	.63

Note. *** $p < .001$.

B.2 Sex Differences in Hemispheric Asymmetry for Global-Local Processing

We included the between-subjects factor of Sex in the ANOVA conducted in the Results section of Chapter 4 (see Section 4.3.3) to examine whether sex influenced the group-level findings. The main effects and interaction effects for the between-subjects factor of Sex are presented here in the supplementary materials. All other main effects and interaction effects are presented in the paper.

An omnibus mixed-design ANOVA was first conducted. The independent variables included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF), and two between-subjects predictors: Age Group (young, older) and Sex (female, male). Two follow-up repeated-measures ANOVAs were conducted separately for young participants and older participants to examine further sex differences in each of the two age groups. The independent variables included two within-subjects predictors: Level (global, local) and Visual Field (LVF, RVF), and one between-subjects predictor: Sex (female, male). Sex differences in the global-local processing bias would be indicated by a significant two-way interaction between Level (global, local) and Sex (female, male), and sex differences in hemispheric asymmetry for the global-local processing would be indicated by a significant three-way interaction between Level (global, local), Visual Field

(LVF, RVF), and Sex (female, male). Bonferroni-corrected *p* values and mean difference (MD) in milliseconds (ms) were reported in the post hoc pairwise comparisons.

B.2.1 Omnibus ANOVA

The omnibus ANOVA indicated there were significant interactions for Level × Sex and Level × Age Group × Sex. These findings indicated that sex may modulate the findings of an age-related local processing bias as reported in Part 1 of the paper. The significant three-way interactions for Level × Age Group × Sex were further examined in two follow-up repeated-measures ANOVAs for each of the two age groups.

There was no significant main effect for Sex, nor were there significant interactions for Level × Visual Field × Sex, Level × Visual Field × Age Group × Sex, or other interactions involving the between-subjects predictor Sex. These findings indicated that there were no sex differences in hemispheric asymmetry for global-local processing in either young participants or older participants. See Table B.2 for the statistics.

B.2.2 Follow-Up ANOVA for Young Participants

The follow-up ANOVA for young participants indicated there was a significant Visual Field × Sex interaction. However, none of the post hoc pairwise comparisons for the Visual Field × Sex interaction in young participants reached significance after the Bonferroni corrections (all *p*s ≥ .17). There was no significant main effect for Sex, nor were there significant interactions for Level × Sex, or Level × Visual Field × Sex. These findings indicated that young females and young males did not differ in their overall performance for detecting global targets as compared to local targets, as both groups demonstrated comparable performance for detecting global targets and local targets. Additionally, young females and young males did not differ in hemispheric asymmetry for global-local processing. See Table B.2 for the statistics, and Panels 1 and 3 in Figure B.1 for the estimated marginal means.

B.2.3 Follow-Up ANOVA for Older Participants

The follow-up ANOVA for older participants indicated a significant interaction for Level × Sex. There was no significant main effect for Sex, nor were there significant interactions for Visual Field × Sex or Level × Visual Field × Sex. Post hoc pairwise comparisons for the significant interaction for Level × Sex indicated that:

(1) older females and older males did not differ in their performance for detecting global targets after the Bonferroni corrections (MD = 12.21 ms, 95% [–38.02, 62.44], SE = 18.37, t = .67, p = 1.00, d = .17), nor for detecting local targets (MD = –50.04 ms, 95% [–110.93, 10.85], SE = 22.26, t = –2.25, p = .17, d = .64);

(2) older females and older males were faster in detecting local targets compared to global targets (older females: MD = 128.98 ms, 95% [93.33, 164.64], SE = 13.04, t = 9.90, p = .03, d = 1.01; older males: MD = 116.77 ms, 95% [62.81, 170.73], SE = 19.73, t = 5.92, p < .001, d = 1.49).

These findings indicated that older females and older males did not differ in their overall performance for detecting global targets as compared to local targets, as both groups demonstrated better performance for detecting local targets compared to global targets. Additionally, older females and older males did not differ in hemispheric asymmetry for global-local processing. See Table B.2 for the statistics, Panels 2 and 3 in Figure B.1 for the estimated marginal means.

Table B.2

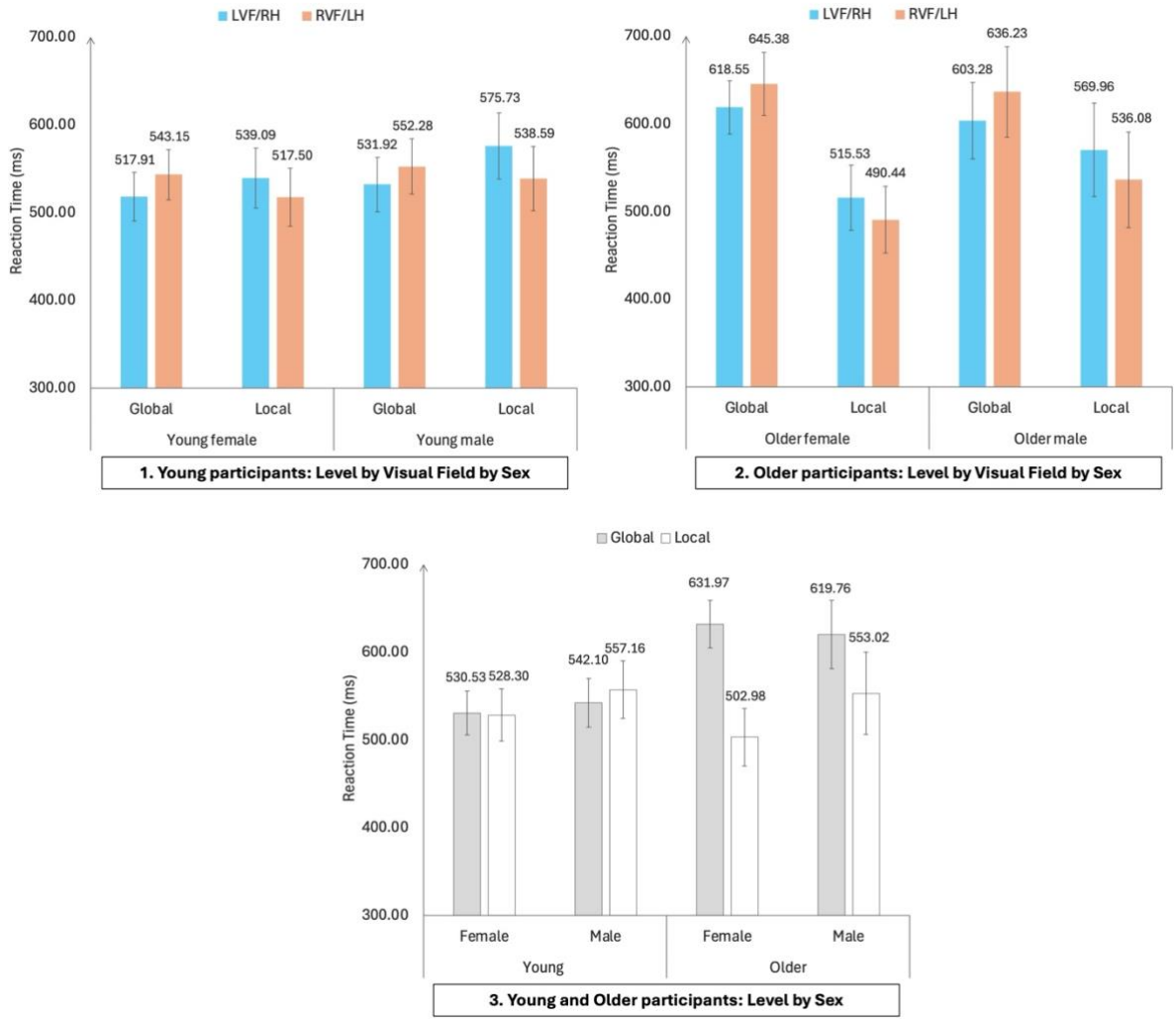
Sex Differences in Hemispheric Asymmetry for Global-Local Processing: Omnibus and Follow-Up ANOVAs

Effects	*df*	*F*	*p*	η^2
Omnibus ANOVA for both age groups				
Level	1	68.09	< .001***	.27
Visual Field	1	0.35	.56	.002
Age Group	1	8.236	.005**	.04
Sex	1	2.25	.14	.01
Level × Visual Field	1	86.26	< .001***	.32
Level × Age Group	1	88.54	< .001***	.33
Level × Sex	1	12.88	< .001***	.02
Visual Field × Age Group	1	0.45	.51	.002
Visual Field × Sex	1	1.23	.27	.007
Age Group × Sex	1	0.002	.96	< .001
Level × Visual Field × Age Group	1	0.361	.55	.002
Level × Visual Field × Sex	1	1.13	.29	.006
Level × Age Group × Sex	1	4.11	**.04***	.02
Visual Field × Age Group × Sex	1	0.72	.39	.004
Level × Visual Field × Age Group × Sex	1	0.03	.86	< .001
Follow-up ANOVA for young participants				
Level	1	1.48	.23	.01
Visual Field	1	1.65	.20	.01
Sex	1	1.76	.19	.01
Level × Visual Field	1	80.93	< .001***	.39
Level × Sex	1	2.69	.10	.02
Visual Field × Sex	1	3.99	**.048***	.03
Level × Visual Field × Sex	1	0.85	.36	.007
Follow-up ANOVA for older participants				
Level	1	73.85	< .001***	.57
Visual Field	1	0.002	.97	< .001
Sex	1	1.25	.27	.02
Level × Visual Field	1	24.01	< .001***	.30
Level × Sex	1	7.47	**.008****	.12
Visual Field × Sex	1	0.02	.90	< .001
Level × Visual Field × Sex	1	0.38	.54	.007

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

Figure B.1

Sex Differences in Hemispheric Asymmetry for Global-Local Processing: Estimated Marginal Means for Reaction Times



Note. LVF/RH = left visual field/right hemisphere; RVF/LH = right visual field/left hemisphere. Error bars represent Bonferroni-corrected 95% confidence intervals. None of the estimated marginal mean contrasts in each of the two age groups reached statistical significance.

B.2.4 Summary and Discussion

Overall, our findings indicated that sex did not influence the group-level findings presented in the Results section of Chapter 4 (see Section 4.3.3). First, there were no sex differences in hemispheric asymmetry for global-local processing. Specifically, both young and older participants were significantly faster in detecting global targets in the

LVF/RH compared to the RVF/LH (i.e., RH specialisation for global processing) and were significantly faster in detecting local letters in the RVF/LH compared to the LVF/RH (i.e., LH specialisation for local processing). Importantly, these hemispheric asymmetry patterns did not differ between females and males. Second, sex did not modulate the age-related local-processing bias. Specifically, the performance of young females and young males was consistently comparable for detection of both global targets and local targets. Likewise, the performance of older females and older males was consistently faster for detection of local targets compared to global targets.

Sex differences in hemispheric asymmetry for global-local processing remain largely underexplored, with only two studies directly examining this question (Roalf et al., 2006; Hausinger & Pletzer, 2021), and with findings that were inconsistent. Roalf et al. conducted an event-related potentials study and found that it was females, rather than males, who demonstrated greater LH lateralised activation for local processing at the P100 component, whereas neither sex demonstrated significant RH specialisation for global processing. Hausinger and Pletzer conducted a behavioural study and found no significant sex differences in RH specialisation for global processing or LH specialisation for local processing.

We believe that the data we have presented in these supplementary materials can serve as a useful starting point for further research on individual differences in hemispheric asymmetry for global-local processing. However, our finding that there were no sex differences in hemispheric asymmetry for global-local processing should be interpreted with caution. First, it has been suggested that sex differences in functional hemispheric asymmetry may be modulated by changes in sex hormone levels (Hausmann, 2017; Hodgetts & Hausmann, 2025). As the study presented in Chapter 4 was not designed to examine sex differences, we did not control for the menstrual cycle of the young female participants, the menopausal status of older female participants, nor the use of hormone-related medication. Second, there were marginal effects suggesting that sex may modulate the age-related local-processing bias in older adults. However, these effects did not reach significance after the Bonferroni corrections. These marginal effects may have been due to the unequal sample sizes between the two sex groups in

our older participants sample (39 older females, 19 older males). We suggest that future research with larger and more balanced sample sizes is warranted to examine systematically sex differences in hemispheric asymmetry for global-local processing.

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