Visual Illusions as a Tool to Study Context Integration and Pictorial Depth Perception Across Methods, Expertise, and Lifespan

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Declaration

I declare that this thesis is entirely my own work completed under the supervision of Professor Trevor Crawford, Dr Calum Hartley, and Dr Sally Linkenauger. None of this thesis has been submitted elsewhere in support of an application for the award of a higher degree. Also, please note that parts of this thesis that have either been published, or submitted for publication, in academic journals during this doctoral degree have been indicated in the statement of authorship chapter.

Signed: R. Wincza

Date: 24/9/2024

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Statement of Authorship

As the first author of all the publishable works within this thesis, whether they are already published (Chapter II and Chapter VI) or submitted for publication (Chapter V), or soon to be submitted (Chapter IV), my contributions encompassed theoretical conceptualization, study design, data collection, and analysis, and submission for publication. This work transpired under the close guidance of Professor Trevor Crawford, Dr Calum Hartley, and Dr Sally Linkenauger, who not only provided theoretical feedback but also offered valuable insights into the manuscripts. Dr Sally Linkenauger's role also included the coding of the experiments described in Chapters III, IV, and VI. Chapter V, exploring the relationship between medical image perception and susceptibility to VIs, was a collaborative effort with Dr Tim Donovan (Cumbria University), who provided feedback on the manuscript and actively assisted in data collection. Chapter VI, delving into susceptibility to VIs in Parkinson’s disorder, was a collaboration with Dr Megan Readman (University of Liverpool). Dr Readman not only granted access to her database of Parkinsonian patients but also contributed theoretical insights and provided feedback on the manuscript. Moreover, she actively participated in the submission process. Jerome Fenton-Romdhani, an undergraduate student and the third author of the systematic review (Chapter II), significantly contributed to conducting the systematic search. Dr Xiaoyun Chen has contributed to parts of the Chapter III, which were not included in this thesis. Furthermore, undergraduate students Maha Sweetha Singaravelu Shanmugam and Tom McMurty, the third and fourth authors of the study on sex differences across methods (Chapter IV), respectively, played active roles in data collection for this and other studies (supported some of the data collection for study described in Chapter V). Lastly, undergraduate student Matthew Turner was also involved in the data collection process on projects which were eventually not included in this PhD thesis.

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(b) The student can incorporate this paper within the thesis.

(c) The contribution of all co-authors for each paper equals 100% minus the contribution of the student.

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AI Statement

To minimise grammar errors throughout the thesis, Grammarly and Artificial Intelligence (AI), specifically ChatGPT, were utilised. Grammarly was applied consistently throughout the entire thesis, while AI was employed to enhance the English quality in most sections, excluding Chapter II and Chapter VI in their entirety. A single command was used to do so, it simply said ‘Improve English’. None of the thesis content was generated by AI or any other third party.

COVID-19 Statement

Work on this PhD was significantly affected by the COVID-19 pandemic. The author spent his entire first year working remotely from Poland due to the restrictions at the time, which had a substantial effect on the author and his work. Also, his second year was largely influenced by the ongoing COVID-19 pandemic (the outbreak of the Omicron variant). Furthermore, many of the initial plans and ideas had to be amended and changed throughout the pandemic and post-pandemic times. It affected the data collection – some of the data had to be collected remotely, which posed additional difficulties and a need for adjustment, as well as making the data collection much slower. Also, to the author's big regret, much of the developmental work was significantly slowed and even halted due to the post-pandemic difficulties in obtaining data at schools and nurseries, resulting in an inability to collect sufficient amounts of data to run the other planned studies. The author would therefore like to draw attention to the fact that some of the shortcomings of this thesis were due to aspects beyond his control.

Thesis Abstract

Visual illusions (VIs) offer a unique lens through which one can explore human context integration and pictorial depth perception. Previously VIs have been used to, for example, uncover deficits in context integration in schizophrenia, as well as its development in children, or differences between vision for action and vision for perception. In this thesis, it was intended to investigate methodological discrepancies observed in previous research, as well as the role of expertise, sex and development across lifespan in susceptibility to VIs. In doing so, this doctoral thesis presents the inaugural systematic review of children's susceptibility to VIs (Chapter II). It reveals that children's susceptibility to certain VIs, such as the Ebbinghaus and Ponzo illusions increases with age, but decreases for the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions. Furthermore, it underscores the possibility that children's responses are likely influenced by response biases. Moreover, it highlights that many previous findings in the field are contingent upon the specific methodologies and stimuli employed. However, a consistent developmental trend emerges with the Muller-Lyer illusion across various experimental conditions. Experiments I and II (Chapters III and IV) delve into methodological disparities between children and adults. In Experiment I, across two different methods, children were not shown to be less susceptible to the Ebbinghaus illusion compared to adults. However, in Experiment II, it was demonstrated that differing methodologies can yield disparate results across sexes. Notably, during Ebbinghaus illusion testing, males exhibit diminished susceptibility to this illusion, particularly under a specific version of the 2-alternative forced-choice method. Additionally, there is a substantial difference in the magnitude of the Muller-Lyer illusion when assessed via the method of adjustment versus the 2-alternative forced-choice method, with greater susceptibility observed in the former. Experiment 3 in Chapter V examines the influence of visual expertise, which was argued to be a potential factor shaping children's susceptibility in the systematic review. We studied

radiologists' and radiographers' susceptibility to a range of geometrical VIs, including the Ebbinghaus and Ponzo. This sample was selected as medical image interpretation relies on strong perceptual skills, which were hypothesised to be linked to VI susceptibility. The findings suggest that individuals with visual expertise in medical image interpretation are less prone to VIs, underscoring the significance of expertise in context integration and pictorial depth perception. Finally, following the insights from the systematic review regarding the role of brain changes in susceptibility to VIs, Experiment 4 in Chapter VI explores the connection between Parkinson's disorder – which manifests specific brain abnormalities including basal ganglia dysfunction and dopamine reduction — and visual anomalies. Collectively, it was observed that context integration remains intact in Parkinson's disorder, suggesting that basal ganglia and dopamine (which are compromised in this condition) are not linked to VI susceptibility. Collectively, the discoveries in this thesis hold profound implications for advancing our understanding of context integration, pictorial depth perception, and the broader field of VI research. Firstly, it urges future research to consider the methodology in use, and its implications for the obtained findings. Furthermore, findings regarding susceptibility trends ought to be revisited, as context integration and pictorial depth perception are likely to develop before the age of seven years. Finally, the findings concerning reduced susceptibility to VIs amongst experts in medical image interpretation suggest that alongside changes in top-down perception, the training and expertise of radiologists and radiographers also lead to changes in bottom-up perception – as manifested by their reduced VIs susceptibility.

Keywords: Ebbinghaus illusion, Muller-Lyer illusion, Ponzo illusion, Poggendorff illusion, Vertical-Horizontal illusion, development, Parkinson's disorder, radiology, methodological differences

Chapter I

General Introduction and Problem Statement

For most of us, since the moment we are born, we start perceiving the world around us. Every day, we open our eyes, we start perceiving; we see shapes, colour, motion – everything that surrounds us. We do so almost effortlessly. And because we perceive for many hours a day, every day of our lives, we – as humans – could be considered visual experts. Yet, as in many other fields of expertise, like chess or football, even the best experts make mistakes. It should be, therefore, unsurprising that even vision and perception are prone to failure. One such example is a visual illusion (VIs). Put simply, a VI occurs when what we perceive does not correspond to the real, physical properties of what is *really* there. Consider the example of the Ebbinghaus illusion – two identically sized circles are perceived as different sizes due to the array of surrounding circles (e.g., Doherty et al., 2010). The circle that appears as larger is surrounded by a set of smaller circles than itself, and the circle that is surrounded by a set of circles larger than itself is perceived as smaller. Because VIs fool our vision and perception, they offer a unique window into the study of human (and non-human, e.g., Feng et al., 2018) visual perception (Notredame et al., 2014), allowing us to study how context is integrated and how pictorial depth is perceived. Context integration refers to how different elements of the visual scene are combined together in order to form a coherent picture (Kaldy & Kovacs, 2003), while pictorial depth refers to the ability to perceive depth in 2-D images – the assumption that despite being portrayed on a flat plane, the physical relationships between different parts of an image correspond to physical relationships in a 3-D world (Jahoda & McGurk, 1974).

Many VIs (such as the Ebbinghaus or Ponzo illusions) are thought to rely on top-down influences, or bottom-up influences (like the Simultaneous Brightness illusion, King et al., 2017) which is another way of uncovering perception of visual scenes. Top-down and bottom-up influences refer to how we process perceptual information. Top-down refers to perceiving the whole (the forest) before its parts (the trees) with possible inputs from memory and earlier experiences, while bottom-up influences are more stimulus-driven (seeing trees before the forest; King et al., 2017). For example, in the context of the Ebbinghaus illusion, linking the surrounding circles and the inner target circles in a single percept (global percept), causes the perceiver to incorrectly perceive the sizes of the targets. However, if perceived locally, i.e., the surroundings are derived from the global picture and perceptual focus is only on the targets, these should be perceived more accurately. Therefore, studying VIs allow us to understand developmental changes in the perceptual binding of visual elements (i.e., context integration; Kaldy & Kovacs, 2003). Studying the developmental trajectories of susceptibility to VIs can provide insight into how different brain areas that are thought to be linked to susceptibility to VIs (e.g., the role of local gray matter density in the parahippocampal cortex; Axelrod et al., 2017) develop. VIs can show the constraints of the visual system and its underlying neural mechanisms (Gori et al., 2016).

VIs have also been used to show perceptual differences between neurotypically developing children and neurodivergent populations, such as autistic children or children with developmental dyslexia (for a review see Gori et al., 2016), as well as between neurotypical adults and individuals with schizophrenia (for a review see Costa et al., 2022; King et al., 2017). Beyond informing us on how visual perception and its development can differ, VIs are also argued to be potential screening tools for the early identification of disorders or to test the efficacy of treatments (Gori et al., 2016). Finally, susceptibility to VIs does not only rely on perceptual abilities; evidence shows that cognitive factors, such as lapses in attention (Barch et al., 2006) and non-verbal intelligence (Doherty et al., 2010) can affect susceptibility to VIs. Therefore, studying VIs uncovers a range of perceptual, cognitive, and neural aspects of human visual perception, making it a unique and effective tool to study visual perception. Thus, across this doctoral thesis, it is aimed to study how context integration and pictorial depth perception changes (if at all) across development, as a result of sex differences, visual expertise, and brain differences. It will provide evidence whether these two abilities remain static across one's lifespan or whether these are prone to change.

Development of VIs Susceptibility

Many VIs are thought to rely on top-down influences (King et al., 2017), which is another way of uncovering children's perception of visual scenes. Studying visual illusions allows us to understand developmental changes in the perceptual binding (context integration) of visual elements for example in the Ebbinghaus illusion (Kaldy & Kovacs, 2003). Furthermore, studying the developmental trajectories of susceptibility to VIs can be used to provide insight into when certain processes – like the ability to integrate elements of the visual scene together – reaches an adult-like level.

Differences in top-down and bottom-up perception are also evident in visual search abilities. These are also shown to develop with age, as children are slower to detect targets than adults – more specifically, children aged 6 to 7 years of age are thought to have a reduced capacity of the top-down aspect of their attention, while they are more sensitive to some bottom-up aspects such as colour differences (Donnelly et al., 2007). Also, younger children are less able to attend to multiple objects simultaneously compared to older children and adults (Dye & Bavelier, 2010), suggesting that they might not be able to integrate illusory-inducing elements of the scene together, resulting in reduced VI susceptibility.

Furthermore, research shows that children younger than 9 years are less reliant on top-down influences during free visual inspections of scenes (natural and complex images) and focus more on the local parts of stimuli rather than perceiving them holistically (Acik et al., 2010). From this, authors have concluded that bottom-up influences are stronger in younger age, while top-down influences become stronger later in adulthood. Again, these findings indicate the VIs susceptibility might be affected in younger children who do not yet have fully developed their perceptual abilities. Therefore, studying VIs in children provides a unique window into the study of context integration.

Analysis of children's (aged 11-12) free visual inspection of van Gogh paintings revealed differences in eye movement patterns compared to adults (Walker et al., 2017). Specifically, children were more drawn to salient features of the paintings, indicating a stronger role of bottom-up influences, in contrast to adults who focused more on the overall picture, relying more on top-down influences. Interestingly, when informed about important features of the paintings, children tended to exhibit more signs of top-down perception. Therefore, children may adopt a different pattern of visually scanning illusions than neurotypical adults, potentially rendering them less/more susceptible to their illusory effects.

In terms of pictorial depth research, developmental evidence is much more scarce. In a notable example, Jahoda and McGurk (1974) demonstrated that children's ability to accurately judge size in images with pictorial depth improves between the ages of 4 and 10 years. In contrast, spatial accuracy remains low in children under 8 years old, but then quickly advances, achieving adult-like accuracy by around age 10. These findings may signal reduced susceptibility to VIs that rely on depth cues, like the Ebbinghaus illusion (e.g., Doherty et al., 2010).

Although developmental trends in susceptibility to VIs have been a topic of interest since the late 19th century, surprisingly, the evidence concerning the individual illusions and their developmental trajectories remains unclear. Perhaps, even more unsurprisingly, these studies have not yet been summarised in a single systematic review or a meta-analysis. This limits the informative potential of this line of research. Beyond summarising the current state of knowledge, works such as systematic reviews and meta-analyses allow the detection of trends in the literature that otherwise could have been missed. Therefore, it is of utter importance that such a summary of the previous work is conducted to allow for a deeper understanding of how VI susceptibility changes across development.

Potential Confounding Effect of Sex Differences

Sex differences have been documented in a variety of areas. Typically, females are shown to have superior performance on somatosensory and auditory tasks (Peters et al., 2009; Frenzel et al., 2012, respectively). On the contrary, males perform more accurately on navigation and mental rotation tasks (Moffata et al., 1998; Collins & Kimura, 1997, respectively). However, research into sex differences in visual perception is sparse and often under-powered (Shaqiri et al., 2018). Therefore, further research into this area is of high importance.

The most comprehensive study into this topic was conducted by Shaqiri and colleagues (2018). In their study involving fifteen distinct visual tasks and over 870 participants, they observed that males significantly outperformed females in areas such as simple reaction time, visual acuity, visual backward masking, motion direction detection, biological motion, and the Ponzo illusion. However, no significant sex differences were found in contrast detection threshold, visual search, orientation discrimination, the Simon effect, Ebbinghaus illusion, Müller-Lyer illusion, the hallway version of the Ponzo illusion, and the Tilt illusion. The authors concluded that, given the varied nature of the sex effects observed, it is improbable that differences between sexes can be attributed to a single underlying mechanism. More importantly, the authors suggested that future research should be considerate of sex differences in vision research.

Sex differences in top-down and bottom-up perception have been explored in various studies. During free viewing of indoor pictures, females tend to engage in more extensive scanning of the picture compared to males, who typically adopt a more localized viewing approach (Sargezeh et al., 2019). These findings suggest that females demonstrate a higher level of context sensitivity than males, relying more on top-down processes when perceiving scenes. These results align with previous research demonstrating that, overall, females exhibit a greater degree of context sensitivity (Baron-Cohen, 2002; Voyer et al., 1995), indicating a propensity for global processing.

Sex differences in top-down and bottom-up processes are also evident in mental rotation tasks, which are widely recognized as one of the most established differences in cognition (Lauer, Yhang, & Lourenco, 2019). Typically, males outperform females in these tasks (Lauer et al., 2019). Using fMRI, Butler et al. (2006) discovered that males exhibit greater activation across primary sensory cortices, basal ganglia, and precuneus, regions associated with implicit learning and mental imagery, suggesting more automatic responses and a bottom-up (local) approach in males. Conversely, females display increased activity across the dorsal medial prefrontal cortex and other high-order heteromodal cortices, indicating that they engage in mental rotation tasks in a more effortful manner, suggesting a more global, top-down approach (Butler et al., 2006).

In Kimchi, Amishav, and Sulitzeanu-Kenan (2009), it was demonstrated that there is no significant difference between females and males in terms of their global-local processing bias, which refers to their inclination to focus on either global or local elements of a scene. However, when confronted with a misleading global context, females exhibited a higher level of distraction compared to males. Consequently, the authors concluded that females and males possess diverse abilities when it comes to utilizing cognitive strategies to mitigate the distracting effects stemming from the global context. Collectively, these findings illustrate that sex differences in visual processing manifest in both behavioural responses, neural activity, and eye movement patterns. Further research is needed to investigate to what extent sex differences in visual perception affect susceptibility to VIs, and whether these are equally manifested across different methods used.

It is possible that, for some studies in the field, the lack of a balanced ratio between females and males in samples could have influenced their results. For instance, Houghton and Tabachnick (1979), Fry and Craven (1972), and Winch (1907) conducted their studies exclusively on male children. Additionally, the latter two studies investigated the Poggendorff and Vertical-Horizontal illusions, respectively, which were not examined in Chapter IV. This raises the possibility that for these two illusions, sex differences might indeed be present. Furthermore, it is plausible that context integration and the ability to perceive pictorial depth develop at different rates in males and females.

Perceptual Learning and Visual Expertise

A definition of perceptual learning can be extracted from Gibson (1969) and described as "an increase in the ability to extract information from the environment, as a result of experience and practice with stimulation coming from it" (p. 3). Expertise on the other hand can be described as the culmination of a long, intentional process of developing and mastering a specific skill (Ericsson et al., 1996). It is widely argued that achieving expertise in any domain necessitates approximately 10,000 hours of dedicated practice (Van Mullem, 2016). Notably, research indicates that expertise induces structural alterations within the brain (e.g., Chang, 2014; Hill & Schneider, 2006). Given the intricate nature of vision and visual perception, it is reasonable to anticipate that as one's visual expertise advances, their susceptibility to VIs may undergo alteration.

Numerous types of visual expertise have been proposed throughout the years, including areas such as chess and radiology (Reingold & Sheridan, 2012). Perhaps unsurprisingly, experts outperform non-experts in their areas of expertise. Models of expertise, like the holistic processing account (Sheridan & Reingold, 2017) and the cognitive theory of expertise (Gegenfurtner et al., 2023), emphasise the role of top-down influences on visual perception. Experts are able to guide their vision to relevant areas, crucial for the completion of the task.

This ability is underpinned by a greater number of memorised target representations, which help to navigate their attention. Also, the eye movement patterns of experts show that they visually process patterns rather than isolated features (Reingold & Sheridan, 2012), which indicates perceptual tuning towards relevant areas of interest. For example, chess masters were shown to have superior performance in replicating a briefly shown pattern on a chessboard (Chase & Simon, 1973a; 1973b). However, crucially, this performance was not related to memory ability per se, as when the same task was performed with a random positioning of the pieces (i.e., beyond what would be expected in a *normal* game of chess), chess masters no longer showed superior performance. This implies better perceptual encoding for task-relevant domains of expertise, which is supported by previous models of visual expertise.

The two-stage detection model proposed by Swensson (1980) provides a framework to study visual expertise in a domain derived from the area of expertise. The model proposes that radiologists are quick to evaluate large proportions of a medical image, but with developed expertise, which acts as a filter, attention is allocated to areas of interest. Such an approach would suggest strong inputs from top-down influences – attention is directed towards areas where abnormalities are likely to be shown. Furthermore, it suggests that the ability to discard irrelevant areas resembles a bottom-up approach – focusing on the details rather than the global picture. Collectively, this theory suggests that experts in medical image interpretation would potentially exhibit lower susceptibility to VIs as they should be more capable of filtering out the irrelevant context (which, in fact, causes the illusory distortions).

Three reasons as to why visual expertise might lead to reduced susceptibility among radiology experts are proposed – 1) stronger inputs from bottom-up influences, which Chapter V focuses upon, and 2) perceptual rescaling and 3) perceptual learning, which will be discussed here as potentially affecting radiologists' susceptibility to VIs. Radiologists and radiographers are of interest as they are often considered in models of visual expertise (e.g., Sheridan &

Reingold, 2017) – they are known to have a superior ability to detect abnormalities, even if they are presented very quickly (e.g., Evans et al., 2013). Furthermore, they frequently turn 2-D images into 3-D representations of the human body, implying potential effects on their perceptual rescaling ability and pictorial depth perception.

Perceptual rescaling plays a pivotal role in accurately estimating the sizes of objects situated at varying distances in the 3D world (Gregory, 1963, 1968). The human visual system automatically rescales identically sized objects placed at different distances, causing us to perceive them as equally sized, even though they project different visual angles onto the retina. However, this rescaling mechanism becomes inappropriate when perceived depth is not "real" (i.e., it is imaginary or constructed; Yildiz et al., 2022). In such cases, pictorial depth cues send signals to the brain, indicating the presence of "depth" in a flat two-dimensional image, which leads to illusory distortions in size perception. In the field of radiology, successful interpretation of medical images necessitates the ability to perceptually transform a 2D image into a 3D scene, thereby achieving a more lifelike representation of the corresponding part of the human body (e.g., Smoker et al., 1984). Studying illusory distortions in radiologists and radiographers, who frequently turn 2-D images into 3-D scenes, may allow for a greater understanding of perceptual rescaling, and its role in VI susceptibility.

Several well-studied VIs probe viewers' perceptual rescaling and depth perception. A classic example of this visual phenomenon is elicited by the Ponzo illusion, which arises from the automatic perception of depth when converging lines act as depth indicators. When these lines converge more closely at the top of the image, mimicking a vanishing point, the upper line appears more distant. As a result, it seems longer compared to the bottom line, which is identical in length. This occurs because viewers erroneously apply size constancy to counteract the natural tendency of the retinal image to enlarge with increasing distance, resulting in the upper line being perceived as longer (Sperandio & Chouinard, 2015). Similarly, the Muller-

Lyer illusion is also believed to occur due to the “misapplication” of size constancy mechanisms, where the line with inward-pointing arrowheads (typically perceived as longer) is assumed to be farther away, compared to the line with outward-pointing arrowheads (Gregory, 1968). The Ebbinghaus and Shepard Table Tops illusions have also been suggested to rely on depth cues, although these cues may not be strong enough to create a genuine perception of depth (Doherty et al., 2010; Sperandio et al., 2022). These illusions can therefore provide a valuable insight into the role of visual expertise in perceptual rescaling, the ability to perceive pictorial depth, and the ability to filter out irrelevant context.

Visual perceptual learning can occur even unconsciously – without any inputs from attention and awareness (Watanabe et al., 2001). Watanabe and colleagues (2001) showed that despite participants attending a different task, they could still learn to detect motion, which was below the perceptual threshold of visibility. The authors concluded that saliency or relevance is not crucial for learning – repeated exposure, even processed unconsciously, is enough to facilitate perceptual learning. Xiao and colleagues (2008) showed that visual perceptual learning can be transferred to other locations not previously trained upon. Training a specific feature (e.g., contrast) at one location, combined with further training on an unrelated feature or task (e.g., orientation) at a different location, whether concurrently or at a different time, leads to the full transfer of the initial feature learning (e.g., contrast) to the second location. While not previously documented in experts, such by-products of perceptual learning – like the ability to ignore irrelevant context – might still occur and be transferable outside of their area of expertise.

The role of practice and perceptual learning has been documented in VIs research. In an early study by Judd (1902), it was shown that the magnitude of the Muller-Lyer illusion disappears with practice. These results were later corroborated by Rudel and Teuber (1963), who also showed that the illusion’s magnitude is weaker after 80 trials compared to the first 10 trials. Somewhat similar results were obtained by Khorasani et al. (2007), whose results implied a reduction in the illusion’s magnitude, although these results failed to reach significance. Similar results were also shown for non-geometrical VIs, like the size-weight illusion (Ernst, 2009; Flanagan et al., 2008), the curveball illusion (Lee & Choi, 2021), and the tilt illusion (Jeong et al., 2024). Collectively, these studies show that perceptual learning and prolonged exposure affect one’s ability to perceive the world.

By studying experts in medical image interpretation on a task derived from their area of expertise, research can test whether their visual abilities are transferable beyond their area of expertise, which would suggest that perceptual learning occurs as well as transfer of such learning. VIs tasks are, therefore, distinct from a typical medical image search. Furthermore, due to VIs misleading nature, it has a direct link to Kundel’s (2006) criticism of radiologists’ assumptions about their perceptual abilities. Kundel argues that radiologists assume that what they perceive in the picture is an accurate representation of the image’s information, which as presented in light of VIs, is not always the case. The use of VIs would help to establish whether their improved ability to interpret medical images is solely due to better analytical skills (more time spent and quicker localisation of critical areas, memorised schemas of scans without abnormalities) or whether some of the improvements are due to better visual skills.

VIs and the Brain

VIs, including the Ebbinghaus, Ponzo, and Müller-Lyer illusions, persist even when perceived beyond the retina, as demonstrated by their persistence under interocular presentation (Schiller & Tehovnik, 2015). Interocular presentation involves presenting illusion-inducing elements, such as converging lines in the Ponzo illusion, to one eye, and target elements to the other eye, typically in a tachistoscopic manner (briefly to prevent binocular rivalry; Schiller & Tehovnik, 2015). The convergence of the two percepts is thought to occur at the visual cortex (Schiller & Tehovnik, 2015). This observation prompted King and colleagues (2017) and Schiller and Tehovnik (2015) to hypothesize that certain VIs (such as contrast-contrast or illusory line motion illusions) primarily engage the V1 area of the visual cortex, while more complex illusions (such as the Ebbinghaus, Ponzo, and Müller-Lyer illusions) are likely to involve higher areas of the visual cortex (V2, V3, or V4), suggesting a hierarchical processing.

Multiple areas of the brain have been found to play a role in VIs susceptibility. For example, Schwarzkopf, Song, and Rees (2011) discovered that individuals with thinner V1 surface areas exhibit greater susceptibility to Ponzo and Ebbinghaus illusions. Also, GABA levels in the occipital and parietal lobes have been found to significantly influence perception of VIs. However, previous studies did not investigate the role of the dopamine basal ganglia in relation to susceptibility to VIs. Basal ganglia has been linked to inadequate perception of illusory depth (Maschke et al., 2006), therefore suggesting that its activity might be related to VIs susceptibility, especially those relying on depth such as the Ponzo illusion (Gregory, 1963) or the Ebbibnghaus illusion (Doherty et al. 2010). This thesis will investigate it in a group of patients with Parkinson's disorder (PD), who are known to have significantly affected basal ganglia as well as reduced dopamine levels (Maschke et al., 2006). Furthermore, this line of research will extend upon previously studied 'visual illusions' in PD (e.g., Nishio et al. 2018; Sasaki et al., 2022). These 'visual illusions', although sharing identical name, refer to somewhat different perceptual phenomena. Visual illusions occur spontaneously during one's day, making an object appear as smaller or larger (macro-/micropsia), or more or less distant (teleo-/pelopsia) than it is in reality (Nishio et al., 2018) amongst many other distortions. Therefore, the study of geometrical VIs, such as Ebbinghaus or Ponzo illusions, which rely on the same perceptual effects, will provide further insight into the perceptual deficits in PD.

The Contributions of This Thesis

Firstly, the thesis will aim to systematically summarise all of the previous research on developmental trends in susceptibility to a range of VIs (Chapter II). This will provide a starting point for this thesis, as it will then attempt to investigate the shortcomings and issues highlighted by the systematic review. Based on the flaws identified in Chapter II, it will attempt to address these in a developmental study (Chapters III), then addresses similar concerns in adult research (Chapter IV). Furthermore, previous research has not investigated the role of visual expertise and the role of neurodegenerative disorders in the elderly in relation to VIs susceptibility. Therefore, this PhD thesis will attempt to fill this gap in current research. evaluate and expand on former research. It will investigate the concept of visual expertise and its relation to VI susceptibility (Chapter V), and finally highlight the role of neuroanatomy in susceptibility to VIs in a neurodegenerative disorder (Chapter VI). This PhD thesis will show the multitude of factors that relate to how our brain process context and pictorial depth. These lines of research will enrich our understanding of VIs susceptibility and provide insight into how conclusions based on previous research might be affected by the different methodologies used. Finally, this line of research will provide a greater understanding of the role of top-down and bottom-up influences on context integration and pictorial depth perception.

Thesis Construction

Overview of Studies

This doctoral thesis comprises four empirical studies (Chapters III, IV, V, and VI) and a systematic review (Chapter II). Chapter II provides a systematic examination of the developmental studies concerning VIs susceptibility. The findings of this Chapter served as a guiding point for further selection of the studies in this thesis – the highlighted shortcomings of the field were investigated in subsequent chapters. Chapter II focuses on the susceptibility to five extensively researched VIs; the Ebbinghaus, Ponzo, Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions, and explores how this susceptibility develops across childhood. In Chapter III, children aged five to seven years and young adults underwent testing using the Ebbinghaus illusion, employing the method of adjustment and two-way alternative forced-choice paradigm to determine whether these approaches yield divergent results. Chapter IV expands on this research strand by investigating sex differences and methodological variances in susceptibility to the Ebbinghaus and Muller-Lyer illusions in young adults, using three distinct methods. Chapter V adopts a different approach, concentrating on the role of visual expertise in susceptibility to VIs. To explore this, professional experts in medical image interpretation are examined using four different VIs. Lastly, in Chapter VI, susceptibility to VIs is examined with a focus on aging and neurodegenerative disorders. This study, conducted during the COVID-19 pandemic, deviates somewhat from the originally intended trajectory of the thesis.

Rationale for Alternative Format

The studies detailed in this doctoral thesis (Chapters II, III, IV, V, and VI) have been crafted in a format suitable for publication. At the time of submission, Chapters II and VI have already been published in *Cognitive Development* and *Frontiers in Psychology*, respectively. Additionally, at the point of submission, Chapters V has been submitted for peer review at

Scientific Reports. Chapter III constitutes part I of a two-part study (part II involves an eye-tracking study), which will be submitted to publication after its precursor is published (Wincza et al. in preparation). Given that the studies in this thesis align with the rigorous standards of academic publishing, as demonstrated by the recent publication of Chapters II and VI, it was determined that the alternative format would be the most fitting for presenting the conducted studies in this thesis. These studies collectively offer a comprehensive insight into the factors influencing susceptibility to VIs across the lifespan.

Chapter II

Thesis Continuity Statement

While Chapter I provided a brief and general introduction to the field of VI research, Chapter II will provide an in-depth, systematic review of developmental trends in susceptibility to VIs. Despite nearly 130 years of investigation, this line of research has not been systematically summarised in a single publication. In doing so, this Chapter will provide an overview of the field while focusing on five most commonly researched VIs in the field: the Ebbinghaus, Ponzo, Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions. It will also provide the reader with explanations to some of the observed trends, as well as will highlight some of the potential issues with previous research, which go beyond the field of developmental research. In many ways, this Chapter will be guiding the selection of other studies in this thesis, as the subsequent chapters will aim to fill some of the gaps this systematic review has highlighted. This Chapter has been published in *Cognitive Development*.

Wincza, R., Hartley, C., Fenton-Romdhani, J., Linkenauger, S., & Crawford, T. (2024). The development of susceptibility to geometric visual illusions in children–A systematic review. *Cognitive Development*, *69*, 101410. https://doi.org/10.1016/j.cogdev.2023.101410

Abstract

Investigating children's susceptibility to visual illusions (VIs) offers a unique window into the development of human perception. Although research in this field dates back to the seminal work of Binet in 1895, developmental trajectories for many VIs remain unclear. Here, for the very first time, we provide a comprehensive systematic review of research investigating children's susceptibility to five of the most famous VIs: the Ebbinghaus, Ponzo, Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions. Following PRISMA best-practice guidelines, 70 articles were identified across four databases (Scopus, PsycInfo, PsycArticles, and Web of Science). Our findings reveal opposing developmental trends across illusions; the magnitude of the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions tends to decrease with age, while the magnitude of the Ebbinghaus and Ponzo illusions typically increases with age. However, developmental trajectories identified by studies investigating the same illusion can vary dramatically due to substantial variability in methods and stimuli. Researchers are more likely to find decreasing VI magnitude with increasing age when employing the method of adjustment response paradigm, whereas the two-way alternative forced-choice paradigm typically reveals greater VI magnitude with increasing age. These findings suggest that conclusions regarding the development of VI susceptibility may be influenced by how they are studied and implicate the involvement of different cognitive abilities across response methods. These findings will benefit future research in dissociating the role of perceptual (e.g. the maturation of the brain's visual areas) and cognitive factors (e.g., attention span) in pinpointing the development trajectories for VI susceptibility.

Keywords: visual illusions, susceptibility, development, systematic review, visual perception

The Development of Susceptibility to Geometric Visual Illusions in Children – a Systematic Review

A visual illusion (VI) occurs when our perception of an object's physical properties departs from physical reality (Gregory, 1998; Notredame et al., 2014). VIs have been employed by researchers to explore a range of visual mechanisms, including the ventral and dorsal perceptual streams (e.g., Knol et al., 2017), neuroanatomical differences (Schwarzkopf et al., 2011), and abnormalities in visual perception in neuropsychological conditions such as schizophrenia (Costa et al., 2023; King et al., 2017) and autism (Gori et al., 2016). VIs also offer a unique window into the development of human perception, as different VIs are thought to be subserved by different perceptual, cognitive, and neural mechanisms (King et al., 2017). Thus, studies investigating developmental trajectories for VI susceptibility can provide valuable insight into the emergence and maturation of these mechanisms. Here, we provide the very first systematic review of research investigating how susceptibility to a range of VIs evolves over the course of children's development.

Research investigating children's VI susceptibility has advanced our understanding of cognitive development in several important ways. Firstly, VIs provide insight into how human visual perception – including depth perception, size constancy, and spatial perception – develops over time (e.g., Leibowitz & Judish, 1967; Pressey, 1974). Documenting the development of these perceptual mechanisms is essential for understanding how children process the visual world. Research has discovered that children's susceptibility to most VIs changes over time. Curiously, the magnitudes of some VIs appear to *decrease* with age (e.g., the Muller-Lyer; Grzeczkowski et al., 2017), while the magnitudes of others *increase* with age (e.g the Ebbinghaus illusion; Doherty et al., 2010). However, research has yet to explain these contrasting developmental trajectories, and different studies investigating the same illusion can yield conflicting results. For example, it has been reported that the Ponzo illusion both increases (Freud et al., 2021) and decreases (Pressey & Wilson, 1978) in magnitude as children get older. Similar incongruent susceptibility trends have been observed for other VIs, including the Ebbinghaus, Poggendorff, and Vertical-Horizontal illusions (Chouinard et al., 2021; Doherty et al., 2010; Hanley & Zerbolio, 1965). A systematic review of the field is necessary to identify and understand the possible causes of these empirical inconsistencies, which represent a major obstacle to understanding how visual perception develops during childhood.

The objective of this comprehensive systematic review is to identify, synthesise, and evaluate research investigating the development of children's susceptibility to five prominent VIs: the Ebbinghaus, Ponzo, Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions. The findings of this review will consolidate the current state of knowledge regarding developmental susceptibility trends and yield insight into why studies measuring the same illusion observe different developmental trajectories. We will explore whether heterogeneity in extant literature can be attributed to methodological and stimuli inconsistencies and the possibility that differences in children's VI susceptibility could be due to immature responding strategies (rather than differences in perception). Crucially, the results of this review will advance the field and theory-making by disentangling how researchers' methodological decisions impact on children's perception of VIs and their strategy use.

Method

The PRISMA statement (Page et al., 2021) was used to conduct and report our systematic review. No protocol was registered for this review.

Eligibility Criteria

For a study to be included in this systematic review, the following criteria had to be satisfied: 1. Participants must be children (between 3 and 16 years of age) without neurodevelopmental conditions (e.g., autism), mental health conditions (e.g., depression), or vision impairments (e.g., strabismus), 2. The study had to compare samples of differently-aged children, or children and adults, 3. The study had to describe their methodology in sufficient detail (i.e., what method was used to measure children's susceptibility to VIs), 4. The study had to include primary data, 5. Ponzo-like effects, elicited by stimuli other than two horizontal lines (e.g., circles, see Grzeczkowski et al., 2017), were excluded from the review. The rationale for this exclusion was to maintain internal consistency among the reviewed studies, i.e., their versions of the illusion were highly similar (see the 'Variations in Stimuli' section for further discussion), 6. The study had to be written in English.

Search

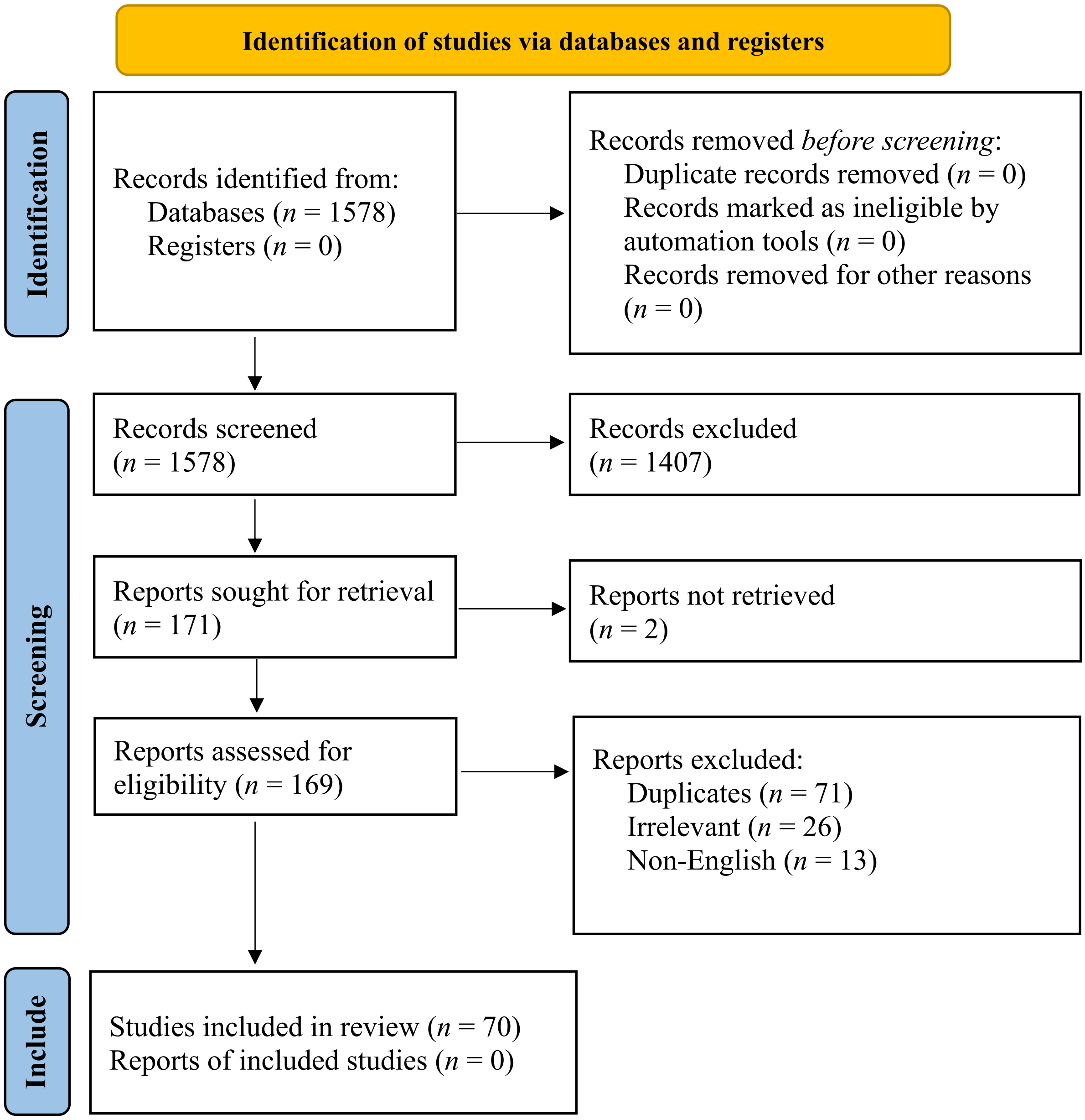
The systematic search was conducted in November 2022. Two strings of keywords were used; "visual illusion*" OR "optical illusion*" OR "ebbinghaus illusion" OR "titchener circles" OR "muller-lyer illusion" OR "muller lyer illusion" OR "poggendorff illusion" OR "ponzo illusion" OR "vertical-horizontal illusion" OR "horizontal-vertical illusion" OR "vertical horizontal illusion" OR "horizontal vertical illusion", and child* OR infant* OR juvenile* OR adolescent* OR kid* OR teen*. The search was conducted on titles and abstracts alone on Scopus, PsycInfo, PsycArticles, and Web of Science databases yielding 736, 609, 58, and 175 articles, of which 52, 77, 8, and 32 met the inclusion criteria, respectively (see Figure 1).

Study Selection

Both the first and third authors searched the databases independently and extracted relevant studies following the inclusion criteria described above. After selecting studies based on their relevance, the reviewers jointly compared extracted studies (n = 169) from all four databases. A high internal agreement between the reviewers was obtained; 94% of studies (n = 159) were selected by both reviewers as being relevant. Discrepancies were re-evaluated by the reviewers and decisions were reached through discussion. Further inspections of full texts led to exclusions due to failure to meet the inclusion criteria (n = 15), duplication (n = 62), and being written in a language other than English (n = 13). Therefore, the final sample consisted of 70 papers reporting 83 trends (either no differences, increasing, or decreasing susceptibility with age).

Figure 1

PRISMA Flow Chart



Note. Summary of literature search and selection process.

Common Methodologies

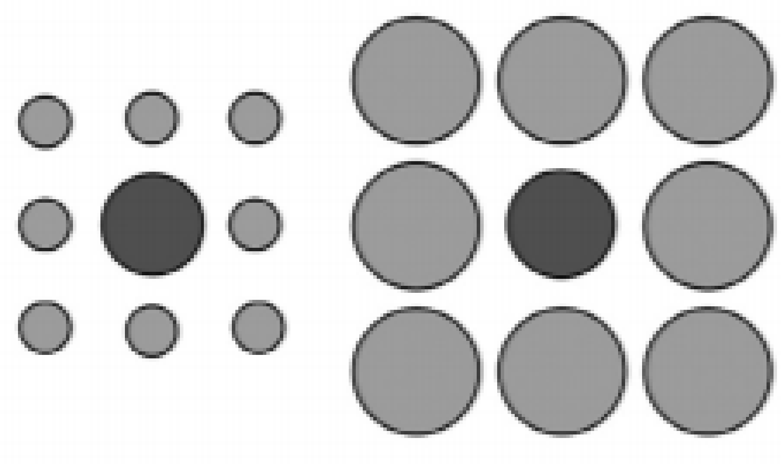
Before discussing the findings of previous studies exploring children's susceptibility to VIs, it is crucial to understand the various response methods they employ such as the two-alternative forced-choice paradigm (2AFC), the method of adjustment, the method of production, the same-different method, and the up-and-down method. Though some of these methods are comparable in nature, differences between them could potentially account for discrepancies in findings between studies investigating the same illusion. Specifically, different response methods may draw upon distinct cognitive mechanisms that develop at different rates. For example, the 2AFC simply requires participants to compare and identify which of two illusory targets is smaller/larger/longer/shorter/darker/brighter (Doherty et al., 2010). By contrast, moving beyond visual discrimination, the method of adjustment requires participants to adjust an illusory target so that it matches another (which is usually very different) on particular physical properties (Hadad, 2018). The method of production is very similar to the method of adjustment, with the minor difference being that the target part of an illusion has to be created by the participant, usually by hand. The same-different method asks participants to indicate whether the target components of illusions are physically identical or different (i.e., binary same/different decision; Barclay & Comalli, 1970). Finally, the up-and-down method tests each participant only once, and stimuli are determined by the previous participant's response (Hanley & Zerbolio, 1965; Weintraub, 1979). For example, if Participant 1 adjusted the target line to be 10 cm, which is their perceived equality, then Participant 2 would view the comparison target to be 10 cm. Then, if that participant found it to be inadequate and adjusted it down or up by one centimetre, the next participant would view the comparison line at 9 cm or 11 cm.

Age Trends in Susceptibility to Visual Illusions

The Ebbinghaus Illusion

Created by Hermann Ebbinghaus, and popularised by Edward Titchener (the illusion is sometimes referred to as the 'Titchener circles'; Roberts et al., 2005), the Ebbinghaus illusion is one of the most studied illusions in developmental research. In its classic form, two identically sized circles are surrounded by larger or smaller circles (see Figure 2). This presentation causes the viewer to overestimate the size of the circle surrounded by smaller circles, perceiving it as larger.

Figure 2
The Ebbinghaus Illusion



Note. A version of the Ebbinghaus illusion as used by Bremner et al. (2016). The middle circle on the left appears larger, however, the middle circle on the right is 6% larger.

Summary of Findings

Many studies using the 2AFC have reported that the magnitude of the Ebbinghaus illusion increases gradually from around 4 or 6 years of age (Doherty et al., 2010; Kaldy, & Kovacs, 2003; Kutuk et al., 2022; Schulze et al., 2022; Thelen & Watt, 2004; Zanuttini, 1996; see Table 1 for an overview of all studies on the Ebbinghaus illusion). Similarly, using the up-and-down method, Weintraub (1979) showed that children's susceptibility to the illusion increases with age. Using the method of adjustment, Mavridis and colleagues (2020) also report an increasing magnitude of the illusion with age in children aged 5 to 15 years. Cross-culturally, the 2AFC has yielded similar age-related trends in Japanese and Chinese children aged 4 to 9 years, although these groups both show a greater illusion effect compared with similarly-aged US or German children (Imada et al., 2013; Schulze et al., 2022). The emergence of the Ebbinghaus illusion may be delayed in Namibian children (until around 9 years) in comparison to UK children, but the direction of their developmental trajectory does not differ (Bremner et al., 2016).

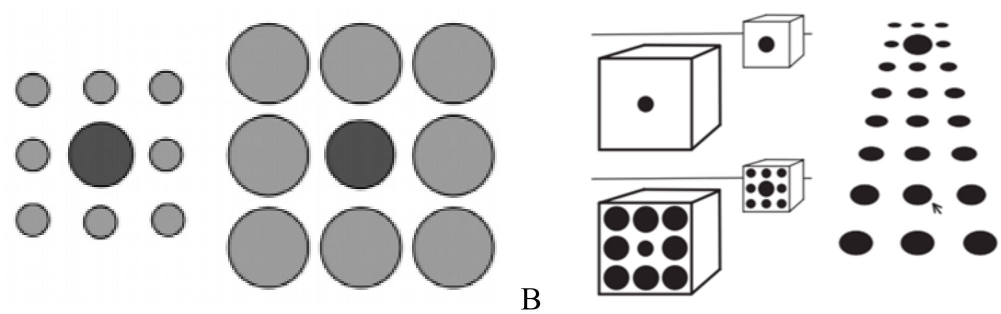
However, the developmental trajectory for the Ebbinghaus illusion susceptibility is not universally consistent (Doherty et al., 2010). Using the method of adjustment, Hanisch et al. (2001) and Duemmler et al. (2008) found no differences between children aged 5-12 years and adults, while Grzeczkowski et al. (2017) showed that susceptibility to the illusion declines with age in participants aged 6 to 81 years of age. Using the 2AFC, Bondarko and Semenov (2004) showed that susceptibility to the Ebbinghaus illusion decreases with age in children aged 6 to 17 years of age. Finally, Hadad (2018) reports a decreasing trend in children aged 4 to 8 years of age using both the 2AFC (though the results failed to reach significance) and method of adjustment (children were more susceptible when the contextual circles were bigger, but no difference was observed when they were smaller).

The decreasing magnitude of the illusion observed by Hadad (2018) and Bondarko and Semenov (2004) may be attributable to their stimuli. Unlike other research using 2AFC to measure the Ebbinghaus illusion (e.g., Doherty et al., 2010), in these two studies, the comparison circle was presented in isolation without any surrounding circles, while the other circle was presented with either smaller or larger surrounding circles (these compositions of the Ebbinghaus illusion allow for distinguishing the role of surroundings on susceptibility). Hadad (2018) reports that for both 2AFC and the method of adjustment, susceptibility declines with age for the larger surroundings. This finding aligns with Coren and Porac (1978), who showed that susceptibility to the Ebbinghaus illusion increases with age if, in the selected set of stimuli, a sole circle is compared against a circle with smaller surroundings. Conversely, comparing a sole circle against a circle with larger surroundings results in decreasing magnitude with age. Similarly, Kaldy and Kovacs (2003) and Zanuttini (1996) report that children aged 4 to 10 years are less susceptible to the Ebbinghaus illusion when an isolated circle is presented next to a circle with larger surroundings. Though not significant, the opposite trend was observed for smaller surroundings, contrary to the findings by Coren and Porac (1978). This discrepancy might be due to employing a different method; Coren and Porac asked children to match a circle from a set of comparison circles to the target (an uncommon method in the field), while the above studies used the 2AFC. Thus, a number of studies indicate that susceptibility to the Ebbinghaus illusion decreases with age when an isolated circle is presented next to a circle with smaller surroundings, but increases when presented next to a circle with larger surroundings. However, it is important to note that these studies do not measure a complete Ebbinghaus illusion, only its reduced form (which is considerably weaker in magnitude; Kaldy & Kovacs, 2003). While such experiments usefully measure the mechanisms of the illusion and the interplay between its parts, the claims made based on those experiments must be carefully extended to the Ebbinghaus illusion as a whole.

Theoretical Explanations

Two of the most prominent psychological theories explaining the Ebbinghaus illusion are proposed by Doherty et al. (2010) and Kaldy and Kovacs (2003). The former proposes that the human visual system's inability to correctly interpret certain depth cues results in perceiving 2D images as 3D scenes, distorting the physical properties of the stimulus. However, in the case of the Ebbinghaus illusion, these cues are not salient enough to cause an explicit perception of depth. Consequently, the circle with smaller surroundings is perceived as further away and is therefore perceived to be bigger (see Figure 3 for a comparison of the classic Ebbinghaus illusions and the Ebbinghaus with more explicit depth cues). By contrast, context sensitivity theory explains the Ebbinghaus illusion in terms of how context is automatically integrated by the human visual system (Kaldy & Kovacs, 2003). This account proposes that top-down influences bind the illusion’s elements in perception, resulting in the distortion of physical properties. These top-down influences are based on expectations, previous knowledge, and the global picture, which results in “seeing the forest before the trees” (i.e., focusing on the whole picture, rather than its parts; Burghoorn et al., 2020). Thus, although the two target circles are judged independently of each other, perception of size is influenced by their surroundings which leads to the illusory effect.

Figure 3
Comparison of the Classical Version of the Ebbinghaus Illusion and an Alternative Version with Explicit Depth Cues



A B

Note. The A version of the Ebbinghaus illusion has no explicit depth cues, compared to the B version on the right. Both versions come from Doherty et al. (2010).

Depth cue and context sensitivity theories have both been employed to explain why the Ebbinghaus illusion’s magnitude appears to increase with age. Kaldy and Kovacs (2003) propose that younger children’s reduced ability to integrate context decreases their susceptibility to the Ebbinghaus illusion – by not binding the illusion’s elements (the target circles and their surroundings) together, children are more accurate in their judgments because they focus on local elements rather than the global picture. This theory is supported by evidence that children younger than 9 years are less reliant on top-down influences during free visual inspections of scenes and focus more on the local parts of stimuli rather than holistic meaning (Acik et al., 2010). Also, in visual search tasks, young children are less able to rely on top-down mechanisms than adults (Donnelly et al., 2007). If children are prone to focus exclusively on the most salient features of the illusion (usually the inner circles are a different colour than the surroundings; e.g., Doherty et al., 2010), this would yield a percept of size that is largely independent of the surroundings. Indeed, Kaldy and Kovacs (2003) showed that 4-year-old children are as accurate as adults in size discrimination when only the middle circles are present with no distractors or pictorial depth, indicating that the ability to discriminate size develops relatively early. The maturation of mechanisms underpinning global perception (which relies on knowledge and expectations) may consequently result in gradually increasing VI susceptibility. Thus, weaker top-down and stronger bottom-up influences could account for children's reduced susceptibility to the Ebbinghaus illusion.

Alternatively, Doherty and colleagues (2010) hypothesise that children's reduced ability to perceive pictorial depth causes them to be less susceptible than adults to the Ebbinghaus illusion. Because the illusion may be contingent on perceiving the target circle surrounded by smaller circles as being further away compared to the target circle with larger surroundings, children's reduced ability to perceive depth may affect their sensitivity. This hypothesis aligns with Bower's (1977) observation that adults perceive a miniature object as being a normal size but further away than it actually is, while children up to six years of age provide more accurate estimates of size and distance. On the other hand, adults are likely to perceive an oversized object as normally-sized but closer in distance, while young children do not. Jahoda and McGurk (1974) showed that children's ability to accurately estimate size in pictures with pictorial depth improves from 4 to 10 years. Conversely, children's spatial accuracy is poor below the age of 8 years, but rapidly increases to reach an adult-like level around 10 years. Therefore, children's reduced ability to integrate depth cues correctly might result in decreased susceptibility to the Ebbinghaus illusion.

To summarise, although the majority of studies suggest that susceptibility to the Ebbinghaus illusion increases with age, differences in stimuli and methodology prevent the developmental trajectory from being accurately and reliably profiled.

Table 1

Studies Investigating the Developmental Trends of Susceptibility to the Ebbinghaus Illusion

Study	Sample	Design	Main finding
Doherty et al. (2010)	151 children aged 4 to 10, 24 adults	2AFC	Illusion's magnitude increases with age.
Hanisch et al. (2001)	34 children aged 5 to 12, 11 adults	Method of adjustment	No differences in susceptibility between children and adults.
Zanuttini (1996)	120 children aged 4 to 10	2AFC	Illusion's magnitude increases with age.
Duemmler et al. (2008)	42 children aged 5 to 9	Method of adjustment	No difference.
Kaldy & Kovacs (2003)	13 children aged 4, 15 adults	2AFC	Illusion's magnitude increases with age.
Bondarko & Semenov (2004)	274 children and adolescents aged 6 to 16 and 23 adults	2AFC	Illusion's magnitude decreases with age.
Weintraub (1979)	386 children aged 6 to 12 years, 36 adults	Up-and-down	Illusion's magnitude increases with age.
Hadad (2018)	40 children aged 4 to 8, 20 adults	Method of adjustment	Illusion's magnitude increases with age when the contextual circles were bigger, but no difference was observed when they were smaller.

Hadad (2018)	12 children aged 4 to 5, 12 adults	2AFC	No significant difference between adults and children (though a reduced illusion size with age was indicated by the results).
Thelen & Watt (2010)	Children aged 4 to 9 and adults.	2AFC	Illusion's magnitude increases with age.
Bremner et al. (2016)	116 Namibian children aged 3 to 17 and 34 Namibian adults, and 37 children aged 3 to 10 were selected from the Doherty et al. (2010) study, and 45 children aged 11 to 17 and 28 adults	2AFC	Illusion's magnitude increases with age for both children in Namibia and the UK though an increase in susceptibility had a later onset in Namibian children.
Imada et al. (2013)	175 children aged 3 to 10 (89 from the USA and 86 from Japan)	2AFC	Illusion's magnitude increases with age. Japanese children show greater illusion.
Coren & Porac (1978)	668 children and adults aged 5 to 70	Selecting a matching circle from a set of comparison circles	An increase with age for smaller surroundings, and a decrease with age for larger surroundings.
Schulze et al. (2022)	261 children aged 4 to 6	2AFC	Illusion's magnitude increases with age.
Mavridis et al. (2020)	297 children aged 5 to 15	Method of adjustment	Illusion's magnitude increases with age.

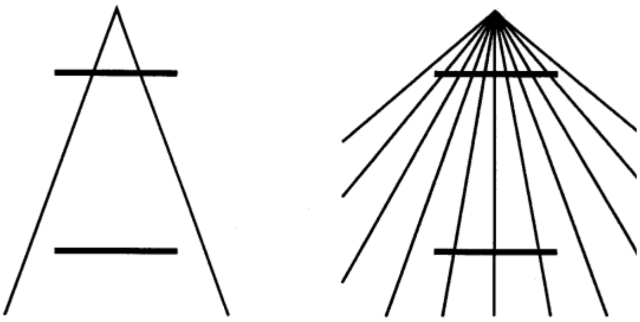
Kutuk et al. (2022)	245 children aged 6 to 10 years of age and 57 adults	2AFC	Illusion’s magnitude increases with age.
Grzeczkowski et al. (2017)	144 participants aged 6 to 81	Method of adjustment	Illusion’s magnitude decreases with age.

Note. A total of 16 studies (Hadad, 2019 reports two separate experiments) on the developmental trajectory of the Ebbinghaus illusion have been included in the review.

The Ponzo Illusion

The Ponzo illusion was actually first discovered by Edmund C. Sanford (Bertamini & Wade, 2023), but is incorrectly credited to Mario Ponzo (e.g., Donaldson & Macpherson, 2017). The illusion consists of two parallel and identically long lines, one of which is perceived to be longer than the other due to converging lines in the background getting closer together (see Figure 4).

Figure 4
The Ponzo Illusion



Note. Two versions of the Ponzo illusion presented by Miller (2001). The line on the top is perceived as longer than the bottom line, however, both lines are equal in length. The example on the left is considered to be the simple version, while the example on the right is considered to be a complex version of the illusion.

Summary of Findings

An early study by Leibowitz and Judisch (1967) using the 2AFC found that the magnitude of the Ponzo illusion increases with age (an overview of all studies on the Ponzo illusion can be found in Table 2). Numerous other studies have corroborated this finding using the same method (Brislin, 1974; Farquhar & Leibowitz, 1971; Freud et al., 2021; Quina & Pollack, 1972; and Wagner, 1977). These studies all employed a vertical version of the illusion, except for Brislin (1974) who used both vertical and horizontal versions, and only differ in their reporting of *when* children start to exhibit an adult-like level of processing – varying from 7 years (Leibowitz & Judish, 1967) to 15 years of age (Farquhar, & Leibowitz, 1971). Pressey (1974) proposes that researchers have identified different ages at which susceptibility to the Ponzo illusion reaches an adult-like level due to variation in stimuli. For example, using stimuli in which the two lines are interrupted by several converging lines elicits an illusion of greater magnitude (as in Farquhar & Leibowitz, 1971; Leibowitz & Judisch, 1967), which is more likely to be perceived at younger ages.

However, as for the Ebbinghaus illusion, studies disagree on the direction of the Ponzo illusion's developmental trajectory. Utilising the method of adjustment, Cretenoud et al. (2020) and Pressey and Wilson (1978) report decreasing illusion magnitude with age for horizontal versions of the illusion. By contrast, using the method of adjustment and a horizontal version of the illusion, Hadad (2018) reports increasing magnitude with age in children aged 4 to 8 years of age, whereas Granrud and Granrud (2004) found no differences between children aged 4 to 5 years and adults. It is worth noting that Cretenoud and colleagues (2020) used a version of the Ponzo illusion where one of the lines was placed outside of the illusory context, which could potentially reduce the strength of the illusion. In adults, such presentations of this illusion affect the perceived size of the top line more than the bottom line due to an increased number of fixations in the upper visual field (Yildiz et al., 2019).

Crucially, developmental trends for the Ponzo illusion may differ depending on its orientation and complexity. Using the up-and-down method, Hanley and Zerbolio (1965) found that children's susceptibility to the Ponzo illusion increases with age when the illusion is vertical, but decreases with age when the illusion is presented horizontally. It is proposed that this discrepancy could be due to the human brain processing these two versions of the illusion differently, meaning that they have separate developmental trajectories. As depth percept for the vertical version is stronger, increasing susceptibility with age could be explained by developmental improvements in children's depth perception (e.g., Jahoda & McGurk, 1974). Conversely, as depth percept is weaker for the horizontal version, younger children's less accurate perception may be attributable to their reduced ability to integrate context (Kaldy & Kovacs, 2003). This may explain why Cretenoud and colleagues (2020) and Pressey and Wilson (1978) found decreasing magnitude with age, as both used the horizontal version of the illusion.

Wagner (1977) reports that in children as young as five years and adults aged 18-22 years, susceptibility to a complex version of the Ponzo illusion increased with age, while susceptibility to a simple version decreased with age. Using a very simplistic horizontal version of the illusion (with only two converging lines), Pressey and Wilson (1978) also reported decreasing susceptibility to the Ponzo illusion with age in children aged 5 to 9 years. However, these data do not align with more recent results (e.g., Hadad, 2018). Though the method of adjustment (used by Hadad, 2018) and method of production (used by Pressey & Wilson, 1978) are almost identical in what they are trying to achieve, they could still elicit differences in observed results. The method of production relies on the participant drawing a line by hand. As the ability to draw relies upon imagery, motor output, and control processes that develop with age (Del Giudice et al., 2000; Toomela, 2002), younger children's less accurate lines may reflect their immature drawing capabilities rather than their susceptibility to the illusion.

Brislin (1974) found increasing susceptibility with age for both vertical and horizontal orientations of the Ponzo illusion. However, these illusions included a greater number of converging lines (lines that bisect the target lines) than most other studies, thereby enhancing depth cues and the illusion's magnitude. Cretenoud and colleagues (2020) tested participants aged 6 to 66 years of age on three versions of the Ponzo illusion (all horizontal): perceptually poor (geometric, with only two converging lines), perceptually moderate (geometric, with multiple converging lines), and perceptually rich (rail track). Perceptually poor and rich contexts both yielded decreasing susceptibility with age. These findings suggest that the horizontal version of the illusion decreases in magnitude with age (Hanley & Zerbolio, 1965), but opposes Wagner's (1977) findings that older children are increasingly susceptible to more complex illusions.

Other potential explanations for heterogeneity in findings across Ponzo illusion studies concern environmental and gender differences. Cultural differences have been found to play a major role in susceptibility to the Ponzo illusion (Brislin & Keating, 1976; Leibowitz & Pick, 1972). For example, the illusion is weaker in magnitude in Ugandan and Guam university students compared to American students, and the illusion is virtually absent in Ugandan villagers (Leibowitz & Pick, 1972). Reduced illusion susceptibility in these cultures has been attributed to differences in their visual experiences (e.g., time spent viewing photographs or pictures), which shape the development of visual perceptual mechanisms (Leibowitz & Pick, 1972). Differences in visual experience may also explain children's reduced susceptibility to the Ponzo illusion; reduced experience viewing 2-dimensional stimuli may cause a weaker percept of depth, resulting in more accurate line length judgements. The Ponzo illusion is also found to be of increased magnitude in females, relative to males (Miller, 1999, 2001). Thus, it is possible that Wagner's (1977) results were influenced by their sampling of only Moroccan males.

Theoretical Explanations

As for the Ebbinghaus illusion, both context sensitivity and the ability to perceive pictorial depth could be proposed as explanations for the Ponzo illusion. Context integration is crucial to the Ponzo illusion; the converging lines may cause illusory effects due to being bound together in perception. Conversely, local and stimulus-driven elements are perceived due to bottom-up influences – focusing on the local elements of stimuli rather than the global picture (Burghoorn et al., 2020). In other words, illusory depth is not perceived if the local elements of the Ponzo illusion are not integrated together, resulting in the two lines appearing to be identical lengths.

The Ponzo illusion is also a traditional example of a depth illusion. Gregory (1963) suggested that the Ponzo illusion is experienced because the perception of depth occurs automatically, and the converging lines are interpreted as depth cues. As the converging lines get closer together at the top of the picture (mimicking a vanishing point), the top line is perceived as being ‘further away’. Because we ‘misapply’ size constancy to combat the retinal image’s tendency to enlarge with distance, the upper line is perceived as longer because it is assumed to be further away (Sperandio & Chouinard, 2015). Recently, Yildiz et al. (2022) proposed that the Ponzo’s depth illusion could be the result of accumulated visual experience. Their theory is underpinned by the Bayesian concept of 'prior probability' - a probability distribution that considers previous knowledge/information about a particular parameter before a process occurs (i.e., previously observed pictures will impact the perception of a new picture). Hence, based on prior experience of viewing depth in pictures, objects in the upper visual field are assumed to be further away, whereas objects in the lower visual field are assumed to be ‘closer’.

Decreased magnitude of the Ponzo illusion in young children could be explained by their reduced ability to integrate context due to weaker top-down influences that bind local elements together in perception. Yildiz et al. (2019) propose that top-down influences impact susceptibility to the Ponzo illusion more than bottom-up influences because gaze is directed more often toward the upper visual field. It is possible that young children explore the top line to a greater extent than adults because it is more perceptually engaging, resulting in reduced susceptibility. This speculation is supported by evidence that the upper visual field favours local (bottom-up) over global (top-down) processing (Thomas & Elias, 2011), and stronger reliance on local elements should reduce the illusion's strength. Alternatively, or additionally, decreased susceptibility may be attributable to young children's reduced ability to perceive pictorial depth (up to the age of approximately seven years; Doherty et al., 2010). In line with these hypotheses, the majority of studies show that susceptibility to the most simple form (geometrical) of the Ponzo illusion increases with age up to around 15 years of age, implying that children's ability to interpret depth cues and/or combine local elements develops through the majority of childhood.

Table 2

Studies Investigating the Developmental Trends of Susceptibility to the Ponzo Illusion

Study	Sample	Design	Main finding
Hanley & Zerbolio (1965)	1422 children aged 3 to 12, and 202 adults	Up-and-down	Illusion's magnitude increases in susceptibility when the illusion is vertical but produces a decrease when the illusion is presented horizontally.
Wagner (1977)	386 participants aged 7 to 22	2AFC	Mixed results depending on factors like whether the person was schooled or lived in an urban or rural setting. Classical Ponzo for urban schooled children – an increase with age.

Leibowitz & Judish (1967)	427 participants aged 3.5 to 88	2AFC	Illusion's magnitude increases with age.
Freud et al. (2021)	17 children aged 5 to 8, 18 adults	2AFC	Illusion's magnitude increases with age.
Cretenoud et al. (2020)	76 participants aged 6 to 66	Method of adjustment	Weak decrease in susceptibility with age (though no significant interactions between different contexts and age).
Quina & Pollack (1972)	70 children aged 7 to 14 and 10 adults	2AFC	Increase and then decrease in susceptibility with age.
Pressey & Wilson (1978)	116 children aged 5 to 9	Method of production	Illusion's magnitude decreases with age.
Hadad (2018)	40 children aged 4 to 8, 20 adults	Method of adjustment	Illusion's magnitude increases with age.
Farquhar & Leibowitz (1971)	168 children aged 3 to 13, 260 older children, and adults	2AFC	Illusion's magnitude increases with age.
Granrud & Granrud (2004)	20 children aged 4 to 5, 40 adults aged 20 to 90	Method of adjustment	No differences between children and adults.
Brislin (1974)	320 participants aged 3 to 22	2AFC	Illusion's magnitude increases with age.

Pressey (1974)	222 children aged 5 to 17	Method of production	Illusion's magnitude decreases with age.

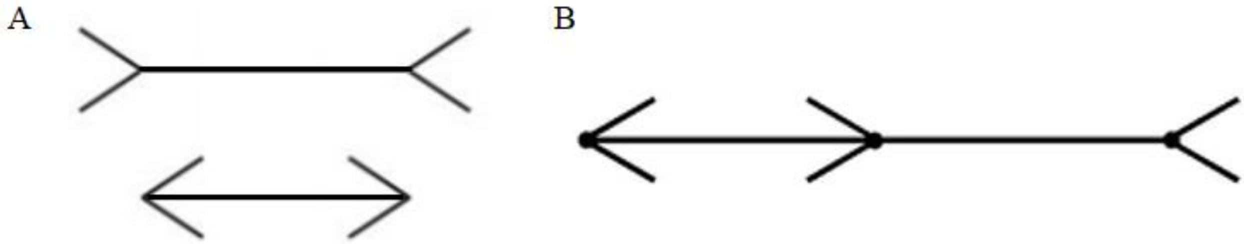
Note. A total of 12 studies on the developmental trajectory of the Ponzo illusion have been included in the review.

The Muller-Lyer Illusion

Created by Franz Carl Muller-Lyer in 1889 (Donaldson & Macpherson, 2017), the Muller-Lyer illusion (see Figure 5) is a popular illusion in developmental research. In its classic form, two equally long horizontal lines are presented in parallel to each other. One of the lines has arrowheads pointing outwards, and one has arrowheads pointing inwards. The arrowheads pointing outwards make the line appear longer. In another version, the illusion is presented as one straight line, with two arrowheads pointing either inwards or outwards, and one arrowhead in the middle pointing in either direction. This version is sometimes referred to as 'Brentano's Muller-Lyer illusion' (Predebon, 1998) or the 'Brentano illusion' (de Grave et al., 2006).

Figure 5

The Muller-Lyer Illusion



Note. A: The classic version of the Muller-Lyer illusion as used by Howe, and Purves (2005a). The top horizontal line appears to be longer, however, both lines are the same length. B: The Brentano version of the Muller-Lyer illusion (de Grave et al., 2006).

Summary of Findings

Age-related findings from studies investigating the Muller-Lyer illusion show an opposite pattern to the Ebbinghaus and Ponzo illusions and tend to be more consistent (an overview of all studies on the Muller-Lyer illusion can be found in Table 3). A number of studies have shown that susceptibility to the Muller-Lyer *decreases*, rather than increases with age, regardless of the method used. In a pioneering study using the same-different method, Binet (1895) showed that children aged 9 to 12 years are more susceptible to the Muller-Lyer illusion than adults. Using the method of adjustment, Rivers (1905) and Walters (1942) attained similar results in children and adolescents aged 6 to 19, while Pinter and Anderson (1916) showed that susceptibility to this illusion decreases with age in children between 6 - 17 years. These results have since been replicated, using identical methods, by Girgus and colleagues (1975), Houghton and Tabachnick (1979), Johnson and Jackson (1974), Grzeczkowski et al. (2017), and Cretenoud et al. (2020). Also, using the method of adjustment, Ahluwalia (1978) reported that Zambian children show a similar developmental trajectory as children from Western countries – younger children are more susceptible to the illusion than older children.

Dawson et al. (1973), Ebert (1976), Pathak and Joshi (1986) and Pollack (1963, 1970) used the 2AFC and obtained analogous results: younger children aged 6 to 12 years were more susceptible to the Muller-Lyer illusion than older children aged 12 to 18 years or adults. Brosvic et al. (2002) and Barclay and Comalli (1970) also showed that susceptibility to the Muller-Lyer decreases with age in children and adolescents aged 3 to 20 years and 8 to 10 years, respectively. These studies employed a paradigm in which participants guessed whether the comparison line was longer, shorter, or equal to the target line. Also, using the up-and-down method, Weintraub and colleagues (1973) reported decreasing susceptibility to the illusion between 8 and 11 years of age. Finally, using a variation of the 2AFC method, Porac and Coren (1981) showed decreasing illusion magnitude with age in children and adolescents aged 5 to 18 years, who in turn were more susceptible to the Muller-Lyer illusion compared to adults.

Nevertheless, as for the Ponzo and Ebbinghaus illusions, variability in stimuli has yielded contrasting developmental trajectories. Employing the 2AFC paradigm, Pollack (1964) showed that the Muller-Lyer illusion decreases in magnitude between 8 to 10 years when all of the illusion's parts are presented simultaneously, however, it increases in magnitude when the different parts (the line and the arrowheads) are presented successively. Pollack argues that when parts of the Muller-Lyer are presented successively, comparisons between the stimulus elements occur over time, drawing upon intellectual functioning and memory. Consequently, older children are more susceptible because they incorporate the stimulus elements together, eliciting the illusion.

Two studies by Tinker (1938) and Hanley and Zerbolio (1965) also report unusual results. In Tinker (1938), using the method of adjustment, children aged 9 to 10 years and adults did not differ in sensitivity to the Muller-Lyer illusion. This finding is surprising as other studies investigating the Muller-Lyer illusion found a decreasing trend using the method of adjustment (Cretenoud et al., 2020; Girgus et al., 1975; Houghton & Tabachnick, 1979; Pinter & Anderson, 1916). Using an up-and-down task, Hanley and Zerbolio (1965) reported that susceptibility to the illusion initially increases with age, peaking at around 7 years, and then gradually declines in magnitude thereafter. These unusual findings are unlikely to be related to methods, as Weintraub and colleagues (1973) employed the same up-and-down task and obtained opposing results. However, Weintraub and colleagues compared a line with arrowheads to a straight line, while Hanley and Zerbolio used a classic version of the illusion (where both lines have arrowheads). Removing arrowheads on one of the two lines may have decreased the strength of the illusion.

Despite contrary illusory trends, perception of the Muller-Lyer illusion may take longer to develop to an adult-like level than the Ebbinghaus illusion; Brosvic and colleagues (2002) showed that perception of the Muller-Lyer reaches an adult level of sensitivity around 15 years of age, whereas the Ebbinghaus approaches an adult level around 11 or 12 years (Doherty et al., 2010). Similarly, Pollack (1963) showed that susceptibility to the Muller-Lyer illusion reaches an adult-like level around 14 years of age. The Muller-Lyer longer to reach an adult-like level because it is more cognitively/perceptually demanding than the Ebbinghaus and

Ponzo illusions. Indeed, the illusion produces the strongest illusory effects in adults when using the method of adjustment, suggesting that it requires greater cognitive or perceptual abilities which younger children may lack (Sperandio et al., 2023).

Theoretical Explanations

Gregory's (1966) explanation for the Muller-Lyer illusion posits that the line with outwards-facing arrowheads is perceived as a concave corner, while the line with inwards-facing arrowheads is perceived as a convex corner (see Figure 6 below). The 'concave' corner is perceived as further away compared to the 'convex' corner, hence it is seen as longer. This view does not, however, account for the Brentano version of the illusion. Alternatively, Bermond and van Heerden (1996) propose that the Muller-Lyer illusion occurs due to imperfections in the human visual system. When viewing the illusion, the human brain calculates 'a weighted mean' of the stimulus' size, leading to an unconscious lengthening of the line with inward arrowheads, and shortening of the line with outward arrowheads. A similar explanation was provided by Howe and Purves (2005), who attributed the Muller-Lyer illusion to a probabilistic strategy that our visual perception employs. When viewing any visual stimulus, size, orientation, and distance are conflated in the retinal image, meaning the stimulus' real-world properties cannot be accurately derived from the retina (Howe & Purves, 2005). Because acting on visual stimuli is crucial for survival, the visual system generates percepts that are based on "the probability distribution of the physical sources of the retinal image", which are sometimes incongruent with the stimulus' actual physical properties (Howe & Purves, 2005, p. 1228). Therefore, the lines constituting the Muller-Lyer illusion may be perceived as different lengths because the visual system inaccurately calculates the probability distributions of the real-world sources of the lines due to the presence of the misleading context of the arrowheads.

Figure 6

The Concave and Convex of the Muller-Lyer Illusion

Note. A classic version of the Muller-Lyer illusion on the left and its version with 3D depth cues (convex on the left and concave on the right; Jennings, 2016).

Curiously, contrary to most empirical evidence, theories proposed by Gregory (1966), Kaldy and Kovacs (2003), and Doherty et al. (2010) would predict that susceptibility to the Muller-Lyer illusion should increase with age. If the inability to perceive depth cues causes children to be less susceptible to the Ebbinghaus and Ponzo illusions, it should also make them less susceptible to the Muller-Lyer illusion. Similarly, if children's ability to visually integrate context is immature (as proposed by Kaldy and Kovacs, 2003), children should be less susceptible to the Muller-Lyer illusion than adults. However, results reported by the majority of studies suggest that susceptibility to the Muller-Lyer illusion is not dependent on depth cues or context integration. If the two lines with arrowheads that constitute the Muller-Lyer illusion are presented next to each other horizontally, rather than parallel (as in Brentano's version, see Figure 8), there would be no depth cues to rely on. Presenting the illusion in this way tests Gregory's theory of convex and concave corners in a 3D world and Doherty et al.'s (2010) hypotheses on pictorial depth. However, children's performance is still less accurate than adults when the illusion is presented in this form (Barclay & Comalli, 1970; Girgus et al., 1975; Hanley & Zerbolio, 1965).

Reduced top-down influences are also an unlikely explanation for increased susceptibility to the Muller-Lyer illusion observed in young children. If younger children are less able to bind together local elements of the illusion, theoretically they should be less susceptible than older children and adults because their length estimates would not be biased by the presence of the arrowheads. It is possible that the distracting elements of the Muller-Lyer illusion are less salient when compared with those in the Ebbinghaus and Ponzo illusions, enabling children to focus on the target line. Alternatively, it could be that the Muller-Lyer illusion is caused by a probabilistic strategy that our visual perception employs (Bermond & van Heerden, 1996; Howe & Purves, 2005). Younger children's performance on the Muller-Lyer may be less accurate because they do not see how stimulus elements, and their possible physical sources, interact based on their statistical relationships. Children may make more frequent perceptual errors when judging the sizes of the two lines because their visual system is relatively immature, still in the process of development, and has received less extensive tuning from visual experience in comparison with an adult's visual system. As perceptual learning occurs (Sagi, 2011; Sagi & Tanne, 1994), children's susceptibility to the Muller-Lyer illusion may decrease as their visual system receives greater exposure to concave and convex structures in their environment (see Figure 6). This explanation is supported by evidence that the Muller-Lyer illusion tends to decrease in strength with practice in adults (Dewar, 1967; Lewis, 1908; Predebon, 2006).

As dominant models of perception (see Sagi, 2011 for an overview) have shown that the magnitude of contextual effects (and perceptual illusions) may vary with sensory precision, the developing, noisier sensory system may rely more on context/priors. Children's increased susceptibility to the Muller-Lyer illusion may therefore not necessarily point to the development of illusion susceptibility, but rather to the increased noise in their developing sensory systems. Another possibility is that children's performance on the Muller-Lyer illusion may differ because it draws upon different perceptual/neural mechanisms compared with the Ebbinghaus and Ponzo illusion. For example, susceptibility to the Ebbinghaus and Ponzo illusion has been linked to surface thickness of the V1 area (Schwarzkopf et al., 2010), while responses in the V1 are consistent with susceptibility to the Muller-Lyer illusion (Ho & Schwarzkopf, 2022). These findings hint that the development of the V1 area affects susceptibility to the Muller-Lyer illusion differently than it does for the Ebbinghaus and Ponzo illusions. However, further research is required to validate this speculative theory.

In summary, most studies indicate that the Muller-Lyer illusion's magnitude decreases as children get older. This developmental trend is opposite to what we have observed for the Ebbinghaus and Ponzo illusions. Furthermore, evidence regarding the Muller-Lyer illusion's developmental trajectory tends to be consistent. This increased level of consistency may be attributed to less variability in stimulus displays, as discussed in more detail below.

Table 3

Studies Investigating the Developmental Trends of Susceptibility to the Muller-Lyer Illusion

Study	Sample	Design	Main finding
Cretenoud et al. (2020)	76 participants aged 6 to 66	Method of adjustment	Weak decrease in magnitude with age, and no interaction between age and context.
Tinker (1938)	35 children aged 9 to 10, and 164 adults	Method of adjustment	No difference between children and adults.
Dawson et al. (1973)	452 children aged 4 to 17	2AFC	Illusion's magnitude decreases with age.
Pitner & Anderson (1907)	250 children aged 6 to 14, and 28 adults	Method of adjustment	Illusion's magnitude decreases with age.
Weintraub et al. (1973)	120 children aged 8 to 11, and 60 adults	Up-and-down	Illusion's magnitude decreases with age.

Brosvic et al. (2002)	140 participants aged 3 to 20	Same-different	Illusion’s magnitude decreases with age.
Pollack (1963)	60 children aged 8 to 12	2AFC	Illusion’s magnitude decreases with age.
Pollack (1964)	96 children aged 8 to 11	2AFC	The illusion decreases with age in simultaneous presentation, but when the parts of the illusion were presented successively the illusion’s magnitude increased with age.
Pollack (1970)	120 children aged 9 to 14, and 20 adults	2AFC	Susceptibility decreases with age when the stimulus is black and white, but no age trend is observed when the illusion is presented in colour.
Barclay & Comalli (1970)	20 children aged 8 to 10, and 20 adults	Same-different	Illusion’s magnitude decreases with age.
Hanley & Zerbolio (1965)	1422 children aged 3 to 12, and 202 adults	Up-and-down	Increase and then decrease with age.
Girgus et al. (1975)	120 children aged 6 to 11, and 40 adults	Method of adjustment	Illusion’s magnitude decreases with age.
Houghton & Tabachnick (1979)	48 boys aged 6 to 9	Method of adjustment	Illusion’s magnitude decreases with age.
Porac & Coren (1981)	688 observers aged 5 to 70	Variation of the 2AFC	Illusion’s magnitude decreases with age.
Binet (1895)	40 children aged 9 to 12 years of age	Same-different	Illusion’s magnitude decreases with age.

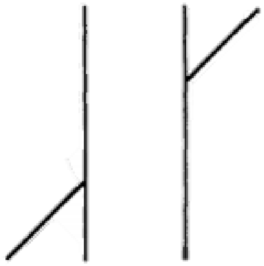
Pathak & Joshi (1986)	350 observers aged 9 to 26 years	2AFC	Illusion's magnitude decreases with age.
Ebert (1976)	50 children aged 6 to 11 and 50 adults	2AFC	Illusion's magnitude decreases with age.
Ahluwalia (1978)	35 children aged 9 to 17 and 10 adults	Method of adjustment	Illusion's magnitude decreases with age.
Johnson & Jackson (1974)	72 children aged 6 to 18	Method of adjustment	Decrease in susceptibility with age but only for the line with arrowheads pointing out.
Rivers (1905)	20 children (ages not specified) and 50 adults	Method of adjustment	Illusion's magnitude decreases with age.
Walters (1942)	1693 children and young adults aged 6 to 19	Method of adjustment	Illusion's magnitude decreases with age.
Grzeczkowski et al. (2017)	144 participants aged 6 to 81	Method of adjustment	Illusion's magnitude decreases with age.

*Note***.** A total of 22 studies on the developmental trajectory of the Muller-Lyer illusion have been included in the review.

The Poggendorff Illusion

Named after Johann Christian Poggendorff, the classic version of the Poggendorff illusion presents the viewer with a structure (usually a rectangle) with lines on each side (see Figure 8). The illusory effect causes the viewer to inaccurately perceive that the two lines are not collinear, when in fact they would join to form a straight line.

Figure 7
The Poggendorff Illusion



Note. A version of the Poggendorff illusion as used by Greist-Bousquet, and Schiffmann (1981). The two oblique lines do not appear to be collinear, when in fact they are.

Summary of Findings

Similar to the Muller-Lyer illusion, the magnitude of the Poggendorff illusion has been found to decrease with age in numerous studies (an overview of all studies on the Poggendorff illusion can be found in Table 4). Using the method of production, Pressey and Sweeney (1970) and Girgus and Coren (1987) found that the illusion's magnitude decreases with age (with the illusion still declining at 15 and 22 years respectively). Using the method of adjustment, Vurpillot (1957), Leibowitz and Gwozdecki (1967), Chouinard et al. (2021), and Tinker (1938) found that children aged 5-14 years show increased susceptibility to the Poggendorff illusion compared to adults. Using the 2AFC method, Hill (1974) also found that the illusion's magnitude decreases with age between 7 and 14 years.

However, akin to the previous VIs, evidence concerning the Poggendorff illusion's developmental trajectory is not universally consistent. Using the method of production, Greist-Bousquet and colleagues (1987) found that children aged 7 to 13 years were equally susceptible to the illusion as adults. Similarly, using a 2AFC method, Spitz and colleagues (1970) found that children aged 9 to 10 years were as susceptible to the illusion as children aged 15 years.

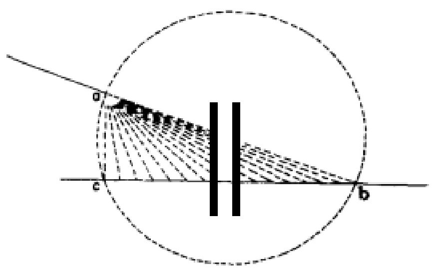
Theoretical Explanations

As for the Ebbinghaus, Ponzo, and Muller-Lyer illusions, it has been proposed that the Poggendorff illusion is caused by depth cues (Gilliam, 1971; Spehar & Gilliam, 2002).

Although these cues are not strong enough to cause an explicit experience of depth, they may still elicit an illusory effect similar to the Ebbinghaus illusion (Gilliam, 1971). The two oblique lines are perceived as receding horizontal lines in a 3D world, while the gap between them is perceived as a plane normal to the line of sight. Hence, collinearity is not assumed, eliciting the illusory percept. However, in recent experiments where pictorial depth cues were added to both the central rectangle and the background, the illusion's strength decreased in adults (Yildiz et al., 2022). Therefore, difficulties in perceiving pictorial depth are an unlikely explanation for children's increased susceptibility to the Poggendorff illusion. Another theoretical explanation for the Poggendorff illusion is that the viewer's attention is restricted to a specific region (like a spotlight focusing on the illusion, see Figure 8 below; Pressey, 1972). When the participant is asked to extend the line in their imagination (so it constitutes a straight line), the participant unconsciously creates multiple lines that are inherently shorter than the 'objective' line. Then, the participant calculates the position of the 'illusory' line based on the mean position of the unconsciously created lines (see Figure 8). Consequently, the line that is traditionally perceived as the true extension of the line is always below the *true* line.

Figure 8

Pressey's Explanation of the Poggendorff Illusion



According to Pressey (1972), younger children are more susceptible to the Poggendorff illusion than older children and adults because they are less visually experienced, resulting in their calculation of the mean extension line deviating further from the true line. Indeed, retinal images are informed by age-related visual experience (Howe & Purves, 2004; Howe et al., 2005). Alternatively, based on Gilliam's (1971) depth processing theory, children may be more susceptible to the Poggendorff illusion than adults because they are unable to perceive pictorial depth to the same extent. This, however, contradicts earlier accounts that the inability to perceive depth cues results in decreased susceptibility to the Ebbinghaus and Ponzo illusions. Finally, the Poggendorff illusion's developmental trajectory cannot be attributed to weaker top-down influences as these should make young children less susceptible, rather than more susceptible. Indeed, Harris and colleagues (2023) demonstrated that adding a secondary task (reading a clock) that should interfere with perception of the Poggendorff illusion due to increased top-down interference does not affect its strength in adults. Furthermore, development of the visual system may reduce the strength of the illusion as fewer perceptual errors are made and processing becomes more refined with increasing experience (Mallenby, 1976). Regardless of the theoretical explanation, it is clear that children's visual perception mechanisms mature with age, reducing their susceptibility to the Poggendorff illusion.

To summarise, as for the Muller-Lyer illusion, the majority of studies report that the magnitude of the Poggendorff illusion decreases with age, irrespective of methodology. Different cut-off ages could be attributed to differences in stimuli, though most response methods and illusion variants appear to yield similar results.

Table 4

Studies Investigating the Developmental Trends of Susceptibility to the Poggendorff Illusion

Study	Sample	Design	Main finding
Girgus & Coren (1987)	60 children aged 6 to 10, 20 adults	Method of production	Illusion's magnitude decreases with age.
Greist-Bousquet et al. (1987)	80 children aged 7 to 13	Method of production	No difference.

Pressey & Sweeney (1970)	100 children aged 8 to 14	Method of production	Illusion's magnitude decreases with age.
Leibowitz & Gwozdecki (1967)	321 participants aged 5 to 80	Method of adjustment	Illusion's magnitude decreases with age.
Spitz et al. (1970)	28 children aged 10 and 28 children aged 15	2AFC	No difference between 10- and 15-year-olds.
Hill (1974)	18 children aged 7 and 10 children aged 14	2AFC	Illusion's magnitude decreases with age.
Tinker (1938)	35 children aged 9 to 10, and 164 adults	Method of adjustment	Illusion's magnitude decreases with age.
Chouinard et al. (2021)	107 children aged 7 to 14	Method of adjustment	Illusion's magnitude decreases with age.
Vurpillot (1957)	Children aged 5 to 12 years old and adults.	Method of adjustment	Illusion's magnitude decreases with age.

Note. A total of 9 studies on the developmental trajectory of the Poggendorff illusion have been included in the review.

The Vertical-Horizontal Illusion

The final illusion included in this review is the Vertical-Horizontal illusion (sometimes known as the Horizontal-Vertical illusion). Adolf Fick is often credited as the inventor of this illusion (e.g., Avery & Day, 1969; Wade, 2014), although Edmund Sandford (1898) and Edward Titchener (1901) could be credited for the L version and inverted T version respectively (see Landwehr, 2016; see Figure 9). In its classic versions, two identically long lines are presented horizontally and vertically to create an inverted T or an L. In both presentations, the horizontal line appears to be shorter than the vertical line.

Figure 9
The Vertical-Horizontal Illusion

Note. The two versions of the Vertical-Horizontal illusion as used by Mamassian and Montalembert (2010). A is the L version, while B is the inverted T version.

Summary of Findings

The developmental trajectory for the Vertical-Horizontal illusion is not yet established (an overview of all studies on the Vertical-Horizontal illusion can be found in Table 5). In early studies using the method of production, Rivers (1905) and Winch (1907) found that children aged 8 to 14 years decreased in susceptibility with increasing age. Using the method of adjustment, Walters (1942) and Seashore and Williams (1930) report similar trends. However, using the method of adjustment, Tinker (1938) found that children aged 9 to 12 years were less susceptible to the Vertical-Horizontal illusion than adults (both for the inverted T and the L versions of the illusion), suggesting increased susceptibility with age.

As for the Ponzo illusion, different versions of the Vertical-Horizontal illusion produce contrasting results. Using the 2AFC method, Fraisse and Vautrey (1956) showed that affording participants unlimited time to inspect the inverted T version of the illusion resulted in decreasing sensitivity between 6 and 10 years. However, under the same conditions, the L version of the illusion yields the opposite developmental trajectory. With tachistoscopic presentation (very brief, ~1sec), susceptibility to the L version of the illusion does not increase with age, and susceptibility to the inverted T slightly decreases with age. The differences in developmental trajectories for these illusion variants and methods of presentation can be attributed to two factors. Firstly, when time is unlimited, children may exhibit decisional and response biases (e.g., trying to 'see through' the illusion rather than visually discriminating the two lines) or limit their cognitive effort. Indeed, Bressan and Kramer (2021) showed that the magnitude of the Ebbinghaus illusion weakens when response time is unlimited. Secondly, it is possible that different neural mechanisms mediate the perception of the two versions, and that these mature at different rates (Hanley & Zerbolio, 1965).

Using the 2AFC method, Dawson et al. (1973) also reported decreasing magnitude of the Vertical-Horizontal illusion (for both the inverted T and L versions) up to 11 years of age in both Hong Kong and US children. However, using the same method, Fry and Craven (1972) did not find a significant difference between adults and young boys aged 5 to 14 years. Brosvic et al. (1993) found that susceptibility to the Vertical-Horizontal illusion declines with age between 3 and 10 years. In this study, participants were shown the illusion, asked to memorise it, and then find it amongst comparators which varied in size. Using the same-different method, Brosvic et al. (2002) report that susceptibility to the Vertical-Horizontal illusion declined with age, reaching adult-like susceptibility at around 15 years of age. Finally, Hanley and Zerbolio (1965) showed increasing magnitude with age using an up-and-down design in children aged 3-12 years of age.

Theoretical Explanations

A classic explanation of the Vertical-Horizontal illusion is that viewers experience a 'vertical bias' – they tend to overestimate vertical lengths compared to horizontal lengths (Jackson & Cormack, 2007; Kunnapas, 1955). However, Hahnel-Peeters et al. (2020) report that only 1% of variance when estimating vertical versus horizontal lengths in a natural environment is explained by sensitivity to the Vertical-Horizontal illusion. Consequently, these authors suggest that the illusory effect arises as a by-product of multiple mechanisms (e.g., the complexity of the surrounding contexts) that work together to generate this specific perceptual ambiguity, rather than a single general mechanism (also see Jackson et al., 2013).

One possibility is that children are more susceptible to the Vertical-Horizontal illusion than adults because they experience a stronger vertical bias under the age of 9 years (Fayt et al., 1992). Children may experience vertical bias to a greater extent than adults because they are usually much shorter than other people in their environment. Given that many things are ‘out of their reach’, and many of the people in their surroundings are significantly taller than them, their estimations of vertical heights may be biased. Also, young children are visually inexperienced compared with adults, meaning their judgements of vertical lengths may be less accurate. Alternatively, Piaget and Morf (1956, as cited in Brosvic et al., 1993) claimed that children’s increased susceptibility to the Vertical-Horizontal illusion may be due to their inability to process spatial coordinates accurately (spatial estimates in children below the age of eight years are less accurate when compared with older children and adults; Jahoda & McGurk 1974).

In summary, although most studies show increased susceptibility to the Vertical-Horizontal illusion in children, its developmental trend is not entirely consistent. As for other illusions, future studies should closely examine how differences between methodologies and stimuli variants influence the developmental trajectory.

Table 5

Studies Investigating the Developmental Trends of Susceptibility to the Vertical-Horizontal Illusion

Study	Sample	Design	Main finding
Brosvic et al. (1993)	120 children aged 3 to 10, and 15 adults	Memorising the stimulus and finding it among comparators	Across all variations of the illusion, the illusions’ magnitude decreases with age.

Brosvic et al. (2002)	140 participants aged 3 to 20	Same-different	Illusion’s magnitude decreases with age.
Fry & Craven (1972)	40 boys aged 5 to 14, and 24 adults	2AFC	No difference.
Winch (1907)	66 boys aged 8 to 14	Method of production	Illusion’s magnitude decreases with age.
Fraisse & Vautrey (1956)	91 children aged 6 to 10, and 47 adults	2AFC	The magnitude of the L form of the illusion increases with age, while the inverted T shows a slight decrease in magnitude with age.
Tinker (1938)	35 children aged 9 to 10, and 164 adults	Method of adjustment	Illusion’s magnitude increases with age.
Dawson et al. (1973)	452 children aged 4 to 17	2AFC	Illusion’s magnitude increases with age.
Hanley & Zerbolio (1965)	1422 children aged 3 to 12, and 202 adults	Up-and-down	Illusion’s magnitude increases with age.
Rivers (1905)	12 children (age unknown) and 15 adults	Method of production	Illusion’s magnitude decreases with age.
Seashore & Williams (1900)	200 children aged 6 to 15 and 73 adults	Method of adjustment	Illusion’s magnitude decreases with age.
Walters (1942)	1693 children and young adults aged 6 to 19	Method of adjustment	Illusion’s magnitude decreases with age.

Note. A total of 11 studies on the developmental trajectory of the Vertical-Horizontal illusion have been included in the review.

Discussion

As shown in this systematic review, susceptibility to VIs changes over the course of children's development. VIs can be broadly categorised based on whether children's susceptibility increases (the Ebbinghaus and Ponzo illusions) or decreases (the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions) with age, and whether susceptibility trends are relatively consistent (the Muller-Lyer and Poggendorff illusions) or inconsistent (the Ebbinghaus, Ponzo, and Vertical-Horizontal illusions). VIs can also be grouped based on whether they are primarily researched using the 2AFC (the Ebbinghaus and Ponzo illusions) or the method of production or adjustment (the Muller-Lyer and Poggendorff illusions).

Primary and Secondary Visual Illusions

A clear pattern emerges from this review; children's susceptibility increases with age for certain illusions but decreases for others. This dichotomy was identified and discussed by Piaget and his collaborators (Lorden et al., 1979; Pressey, 1974). According to Piaget (1969, as cited in Lorden et al., 1979), primary illusions (type I) decrease in magnitude as children get older, while secondary illusions (type II) increase in magnitude. Thus, the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions could be categorised as primary illusions. Perception of type I illusions does not rely on intellectual abilities (Pollack, 1964) and their magnitude correlates with chronological age, rather than mental age (whereas type II illusions show an opposite pattern; Clem & Pollack, 1975). This dichotomy between type I and type II illusions is believed to be caused by 'centration' (Piaget, 1961, 1963, as cited in Cretenoud et al., 2020). Centration occurs due to the overestimation of an object present in the centre of the visual field, as compared to its surroundings. Because primary illusions rely on elements' interactions within a single fixation (Flavell, 1963, as cited in Hanley & Zerbolio, 1965), simultaneous comparison of the elements causes the illusions to occur (Clem & Pollack, 1975).

Therefore, younger children may make more visual centrations compared with older children, causing them to be more susceptible to type I illusions.

The Ebbinghaus and Ponzo illusions can be categorised as secondary illusions (type II), as they are mostly shown to increase in magnitude as children get older. Piaget (1961, 1963, as cited in Cretenoud et al., 2020) proposed that children increase in susceptibility to type II illusions as their cognitive and visual abilities mature (e.g., depth perception, context integration). Type II illusions rely on active exploration and comparisons between an illusion's elements (arguably the Ebbinghaus and Ponzo illusions cover more of the visual field, and involve more elements than other illusions included in this review; Clem & Pollack, 1975; Hanley & Zerbolio, 1965; Pollack, 1964). These explanations align with theoretical claims that young children are less able to integrate context (Kaldy & Kovacs, 2003) or perceive pictorial depth (Doherty et al., 2010), meaning they are less susceptible to type II VIs.

Methodological Differences

Methodological differences may also influence children's susceptibility to VIs at different ages. Response methods most commonly employed by VI studies include the 2AFC, method of adjustment, method of production, same-different method, and the up-and-down method. The two most frequent methods utilised by studies in this review are the 2AFC (n = 43) and the method of adjustment (n = 35). These methods account for 80 out of 83 trends (note that some studies report more than one trend per illusion). Therefore, in line with the division made by Kingdom and Prins (2016), we will refer to the 2AFC, same-different, and up-and-down methods as 'forced-choice paradigms', while the method of adjustment and method of production will be referred to as 'adjusting methods' from now on. Adjusting methods typically measure the magnitude of the illusion (how much larger/smaller the target is compared to the reference), while forced-choice paradigms measure the accuracy/discrimination ability to detect physical differences between targets (for example, is the top or the bottom line longer?).

Comparing these methods across individual illusions reveals a clear pattern in the literature: forced-choice paradigms usually yield an opposite developmental trajectory compared to adjustment methods (excluding the Muller-Lyer and Poggendorff illusions which produce stable results regardless of methodology; see Figures 10 and 11 below).

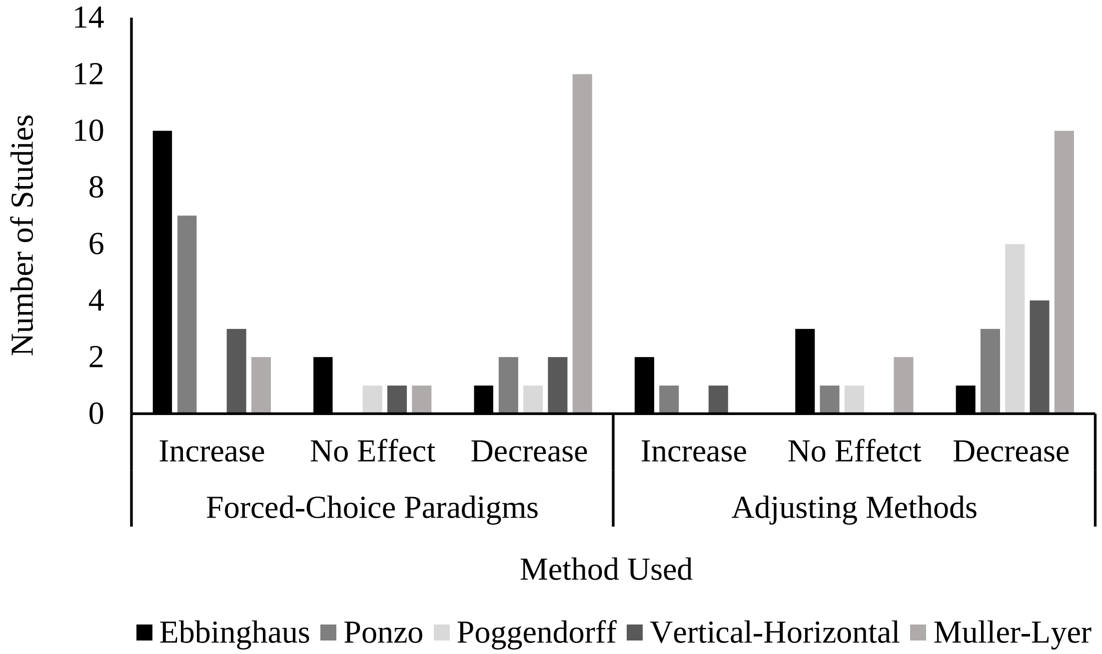
Out of 33 trends for the Ebbinghaus and Ponzo illusions, 20 showed increased susceptibility with age, of which 16 were obtained using forced-choice paradigms (Ebbinghaus $n = 10$; Ponzo $n = 7$). An additional three trends showing increased susceptibility with age were obtained using adjusting methods (two for the Ebbinghaus illusion, and one for the Ponzo illusion), and another was observed using a different method for the Ebbinghaus illusion. For the Vertical-Horizontal illusion, studies employing forced-choice paradigms were more likely to discover increasing susceptibility with age (three studies show increasing magnitude with age, one study shows no difference, and two show decreasing magnitude) compared with adjusting methods that tended to identify decreasing susceptibility with age ($n = 4$), rather than increase ($n = 1$).

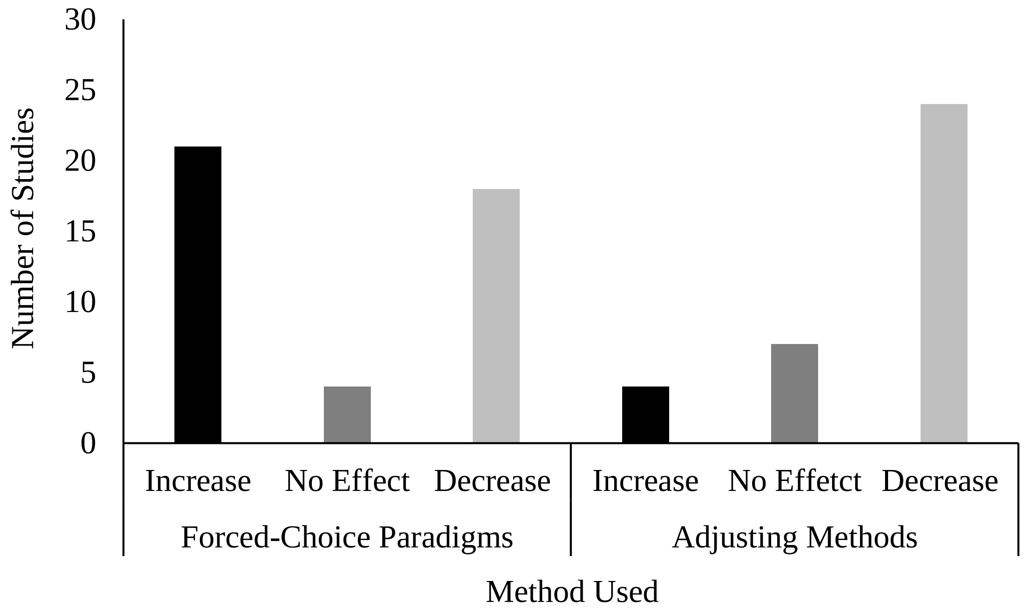
Across all illusions studied with forced-choice paradigms ($n = 45$), illusion magnitude increased with age in 22 cases, decreased with age in 18 cases (of which 12 were for the Muller-Lyer illusion, which has the most clearly defined susceptibility trend), and 4 cases showed no significant age effects. Studies employing adjusting methods mostly found decreasing magnitude with age (24 out of 35 trends) and just four identified increasing magnitude for the Ebbinghaus ($n = 2$), Ponzo, and Vertical-Horizontal illusions. Slightly more studies using the adjusting methods failed to identify age differences ($n = 7$; of which three were obtained for the Ebbinghaus illusion) compared with the forced-choice paradigms ($n = 5$). These findings strongly suggest that differences in response method may contribute to variability in observed findings concerning VI susceptibility.

A potential reason why illusions like the Ebbinghaus or Ponzo are more frequently researched using forced-choice paradigms is that traditional, noncomputer-based experiments using adjusting methods were harder to create than for illusions like the Muller-Lyer and Poggendorff. For the Muller-Lyer and Poggendorff illusions, study findings are more consistent despite variation in children's response methods – sensitivity to these illusions reliably decreases with age. Across 28 trends for the Muller-Lyer illusion, 23 trends indicated decreasing magnitude with age (forced-choice paradigms – 12 trends, adjusting methods – 10 trends, and other methods – 1 trend), increasing magnitude with age was detected in two cases, (both using forced-choice paradigms), and three cases found no age effects (forced-choice paradigms = 1; adjusting methods = 2). For the Poggendorff illusion, forced-choice paradigms found decreasing susceptibility with age in one experiment, while adjusting methods elicited decreasing susceptibility with age in six experiments. These findings suggest that the Muller-Lyer illusion is robust to variations in response method and reliably decreases in magnitude with age. This may also be true for the Poggendorff illusion, although this illusion has only been studied twice using the forced-choice paradigms (with one showing no effect of age).

Figure 10

Developmental Trajectories for Visual Illusion Susceptibility Across Different Methods





Note. For the forced-choice paradigms, 7 trends indicating decreased VI susceptibility with age are assigned to the Muller-Lyer illusion, which has the clearest developmental trajectory of all illusions included in this review.

We also observed that the distribution of methods is uneven between illusions. Illusions producing mostly an increasing trend in susceptibility (the Ebbinghaus and Ponzo illusions) are more commonly researched using forced-choice paradigms (*n* = 22) than adjusting methods (*n* = 11). Conversely, VIs that are often shown to decrease in magnitude with age (the Muller-Lyer and Poggendorff illusions) are mostly researched using adjusting methods (*n* = 19) rather than forced-choice paradigms (*n* = 17), although both illusions show a much more clearly defined susceptibility trend compared to the Ebbinghaus and Ponzo illusions.

Theoretically, if one's susceptibility to an illusion is reduced or increased, the same trend should remain constant despite variations in response method. However, the existing literature investigating VIs clearly demonstrates that this is not the case. Differences between various methods are not well understood as very few studies have examined children's illusion susceptibility using more than one method. In a notable exception, Manning et al. (2017) examined susceptibility to the Ebbinghaus and Muller-Lyer illusions in children aged 6 to 14 years using the same-different method, method of adjustment, and forced-choice paradigms with a roving pedestal (for further details, see Morgan et al., 2013). Their results showed that children did not differ in their susceptibility across different methods. It is, however, important to highlight that children's performance was not compared across different ages, therefore it is unclear whether younger children differed in their performance compared with older children when responding to different methods and/or illusions. In another study, Hadad (2018) compared susceptibility to the Ebbinghaus illusion when using forced-choice paradigms and method of adjustment in children aged 4-8 years and adults. They observed that children were more susceptible to the Ebbinghaus illusion than adults using the method of adjustment, but not forced-choice paradigms.

Finally, the two categories of methods differ in terms of their requirements and outcomes. Adjusting methods require participants to 'match' the target (e.g., the top line in the

Ponzo illusion) with a constant reference (e.g., the bottom line of the Ponzo illusion). The outcome of this ‘matching’ is the magnitude of the perceived illusion, i.e., the physical difference in size between the target and the constant reference. Forced-choice paradigms, on the other hand, measure the ability to discriminate between two sizes (e.g., the two inner circles in the Ebbinghaus illusion). The outcome of this is the proportion of correctly reported differences. Therefore, observed differences in susceptibility between children and adults for some illusions (especially the Ebbinghaus and Ponzo illusion) might be attributable to the different measurements employed and the contrasting challenges they present for children. Further research is required to investigate interactive relationships between different VIs, response methods, and chronological age.

Cognitive Biases and Strategy Use

Studies that utilise adjusting methods and forced-choice paradigms may report different age trends because these tasks draw upon different cognitive mechanisms and biases. There are two key cognitive biases that are relevant to studying VIs; response bias and decisional bias (Morgan et al., 2013). The response bias occurs when one type of answer is systematically preferred over others, despite the stimulus condition (Wetzel et al., 2016). Decisional bias is the strategy adopted by a participant when unsure of their judgements in difficult tasks (Morgan et al., 2013).

Some researchers have argued that forced-choice paradigms may be inadequate for measuring children’s susceptibility to the Ebbinghaus and Ponzo illusions as they are prone to response and decisional biases (Morgan et al., 2013; Kingdom & Prins, 2016). As forced-choice paradigms usually involve a larger number of trials than adjusting methods, repeated exposure to the same illusion may lead to a greater overreliance on perceptual biases due to boredom, tiredness, or perseveration. Furthermore, children may differ from adults in terms of their expectations about the properties of targets (i.e., their threshold for perceiving targets as identical in size may be lower). Finally, children may intentionally or unintentionally adopt a different set of criteria on how to respond to the task (Kingdom & Prins, 2016), which may lead to the appearance of differences in VI susceptibility in comparison with adults. In line with this, children below the age of 10 years show poorer performance on computerised assessments of response bias due to reduced motivation and less effort invested into the task (Courtney et al., 2003). For example, Thelen and Watt (2010) observed that children up to 6 years of age exhibit a tendency to perseverate on the target circle with larger surroundings, regardless of the size of the inner circle. When this effect was controlled for, no differences between children and adults were identified in their susceptibility to the Ebbinghaus illusion. A similar bias could explain why Doherty et al. (2010) found that children aged 4 to 6 years were more sensitive to very small changes (2%) in the Ebbinghaus illusion than adults. Here, children only performed at chance when the display of the illusion was congruent with its illusory effect (i.e., the target circle that is classically perceived as smaller, was in fact physically smaller). For example, children's task might be to always point towards the larger, inner circle. Therefore, in an experiment where in most cases, the 'perceived as larger' circle is physically larger (except when the smaller circle is congruent with the illusion, see above), such display would cause children to appear less susceptible (if they rely on a strategy that involves selecting the large surroundings only), as they would correctly respond in the majority of trials. The findings of Bremner et al. (2016), Imada et al. (2013), Schulze et al. (2022), and Kutuk et al., (2022) could also be subject to similar biases.

There are two explanations for children's perseverative responses in studies of the Ebbinghaus illusion. Firstly, younger children (e.g., 4 to 6 years of age) may try to limit the cognitive effort they expend during the task as visual discrimination of small size differences in VIs over many trials can be fatiguing (Courtney et al., 2003). Therefore, younger children – who tend to have more limited attention spans than adults (Betts et al., 2006) – may at some point start to rely on a response bias strategy rather than visual discrimination. Secondly, children may perseverate on stimuli with larger surroundings due to their preference for more visually stimulating arrays (Braine & Shanks, 1965). Thus, in the Ebbinghaus illusion, children might simply prefer larger surroundings as opposed to having a better ability to discriminate size differences. Consequently, with age-related improvements in general fluid intelligence and sustained attention (Betts et al., 2006; Fry & Hale, 2000), children's performance may become more adult-like because they are able to stay "on-task" for longer (yielding a more valid measure of their visual perception, rather than response strategy use).

For the Ponzo illusion, opportunities for strategy use are perhaps more limited. Most studies employing forced-choice paradigms only manipulate the length of the line that is perceived as further away. As the 'closer' line is presented as both shorter and longer, perseverating to only one type of answer (i.e., repeatedly stating the line is shorter or longer) would result in chance-level performance. However, if children answer correctly when lines are clearly different lengths, their scores would increase, causing them to appear less susceptible to the VI. This could potentially explain why researchers using forced-choice paradigms identified increasing Ponzo illusion susceptibility with age.

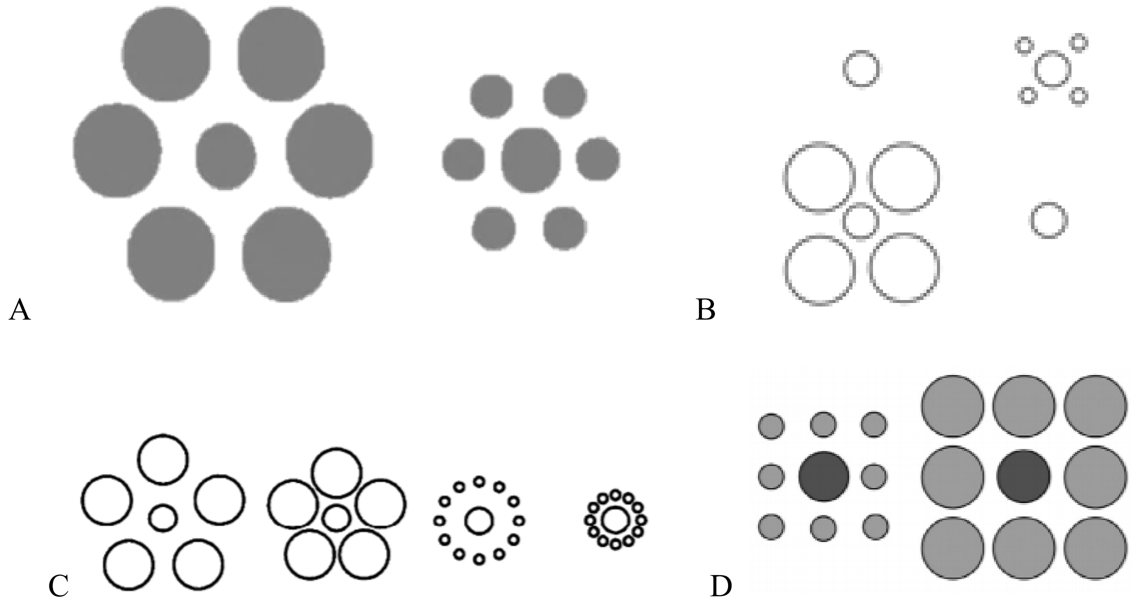
Finally, it may be easier for some children to respond accurately via the method of adjustment than forced-choice paradigms because it allows the participant to indefinitely increase or decrease the target to find the closest match. This response method may favour older participants who are more cognitively skilled, perhaps explaining why most studies that employ adjusting methods have identified decreasing illusion magnitude with increasing age. For example, younger children are less able to attend to multiple objects simultaneously compared to older children and adults (Dye & Bavelier, 2010). Also, visual search abilities are shown to develop with age, as children are slower to detect targets than adults (Donnelly et al., 2007). Furthermore, children's sustained attention increases significantly between the ages of five and nine years (when susceptibility to some illusions, like Ebbinghaus or Ponzo, starts to appear more adult-like; Betts et al., 2006). However, the method of adjustment requires more effort, as participants are required to manipulate sizes, rather than make simple visual discriminations as in forced-choice paradigms (Courtney et al., 2003).

As more studies comparing response methods emerge, current beliefs that children are less or more susceptible to certain illusions may be called into question (especially for the Ebbinghaus and Ponzo illusions). Methodological differences require further investigation to establish whether age-related differences are in fact due to perceptual differences between children and adults, or cognitive and response biases associated with specific tasks.

Variations in Stimuli

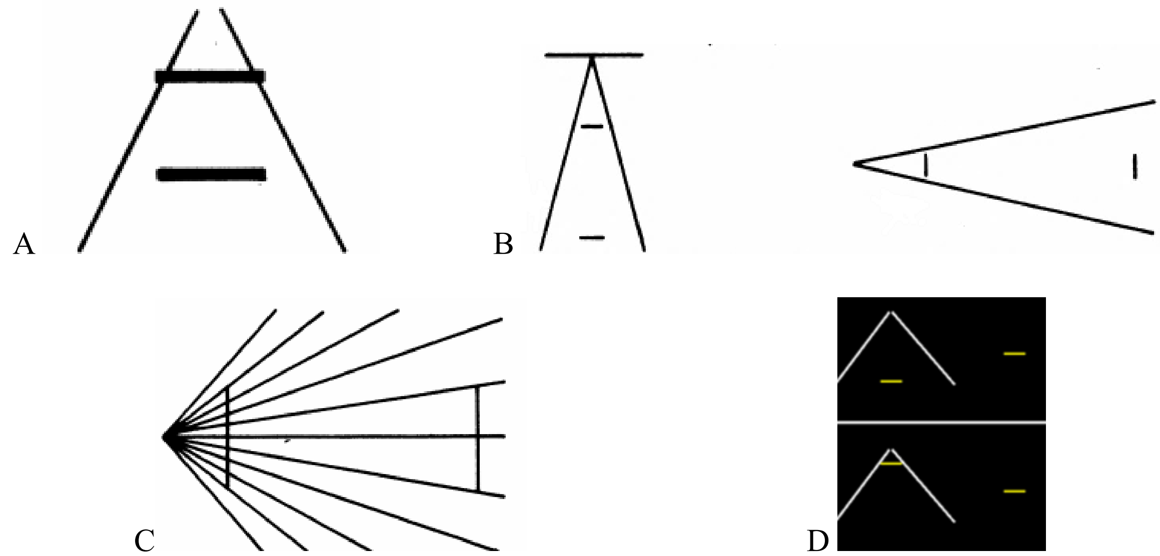
The lack of reliable developmental trends for certain VIs may be attributed to variations in stimuli presented to participants. This is especially relevant to the Ebbinghaus and Ponzo illusions, which allow for more variations compared to the Vertical-Horizontal and Poggendorff illusions. For illustration, different versions of the Ebbinghaus, Ponzo, and Muller-Lyer illusions are presented in Figure 12, Figure 13, and Figure 14 respectively. Notably, while variations of the Ebbinghaus and Ponzo illusion differ markedly in their appearance, variants of the Muller-Lyer illusion are relatively more consistent (perhaps explaining why developmental findings associated with this illusion are more reliable).

Figure 11
The Different Versions of the Ebbinghaus Illusion



Note. Version A, B, C, and D were used by Hadad (2018), Bonadrko and Semenov (2004), Duemmler et al. (2008), and Bremner et al. (2016), respectively.

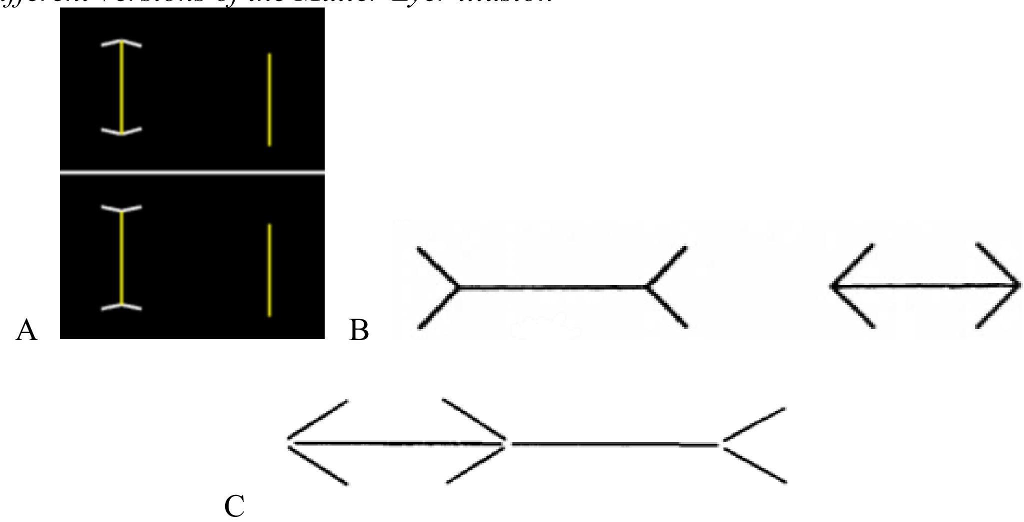
Figure 13
The Different Versions of the Ponzo illusion



Note. Versions A, B, C, and D, as used in studies by Brislin (1974), Hanley and Zerbolio (1965), Leibowitz and Judisch (1967), and Cretenoud et al. (2020), respectively.

Figure 14

The Different Versions of the Muller-Lyer illusion



Note. Versions A, B, and C as used by Cretenoud et al. (2020), Hanley and Zerbolio (1965), and Barclay and Comalli (1970), respectively.

Contrasting result patterns associated with different illusion variants have been noted in the developmental literature. Doherty and colleagues (2010) argue that certain versions of the Ebbinghaus illusion could lead to erroneous findings. If the surroundings are aligned as a tight ring around the target circle, such a display may cause young children (aged approximately 4 to 6 years) to confound the separation between targets and the surrounding circles. For the Ponzo illusion, differences in orientation (Hanley & Zerbolio, 1965) or complexity (Pressey, 1974) can cause different susceptibility trends, leading researchers to propose that illusion variants are subserved by distinct perceptual mechanisms (Greist-Bousquet et al., 1987). Variations in stimuli may also cause differences in illusion complexity, with more perceptually demanding displays (e.g., with more explicit depth) tapping into more sophisticated perceptual mechanisms (e.g., top-down influences) or eliciting these to different extents. In fact, Cretenoud and colleagues (2020) demonstrated that varying the complexity of the Ponzo and Muller-Lyer illusions results in different developmental trajectories and illusion magnitudes. Such differences in stimuli could also explain why studies identify different age thresholds at which children attain adult-like performance, highlighting the need for further research into stimuli variability.

A more philosophical issue is the question of how we should define each particular illusion. For example, what *really* constitutes the Ebbinghaus illusion? Are the circles an essential part of the illusion, or could triangles or squares be used instead? Should the surrounding circles be presented in a tight ring around the middle circle or at an equal distance from the target irrespective of their size? Or does the term 'Ebbinghaus illusion' refer to its illusory effect (i.e., everything that causes illusory enlargement/shrinkage of a stimulus based on its surroundings)? Given that different studies present the same illusion in various ways, future researchers should carefully consider their findings and claims that certain VIs increase or decrease with age, as their reported findings may be unique for their version of an illusion.

Recommendations for Future Research

As highlighted throughout this systematic review, methodological differences are a likely candidate for explaining contradictory findings across studies investigating developmental trajectories for VIs. Therefore, an important objective for future research is to directly assess whether different response methods (e.g., adjusting methods or forced-choice paradigms) consistently yield opposite developmental trends. It would also be beneficial for future research to examine how children respond to different versions of the same illusion, varying their orientations and complexity. This approach will enable researchers to identify whether certain susceptibility trends are illusion-specific, or whether multiple illusions share common features, thus advancing understanding of their underlying cognitive mechanisms (for a recent example, see Cretenoud et al., 2020). Both issues should be investigated with particular attention to gender differences, as these have also been noted to affect susceptibility to VIs (e.g., Miller, 2001).

Although researchers have extensively investigated how saccades (quick and simultaneous movement of both eyes in the same direction, Kaiser & Lappe, 2004) are biased by different VIs (e.g., Muller-Lyer illusion: Bruno et al., 2010; Poggendorff illusion: Melmoth et al., 2015), eye-tracking has been absent from developmental research on VIs to date. The use of eye-tracking could advance understanding of several interesting topics. Firstly, eye-tracking could be used to test the assumption that children sometimes perseverate to the larger surroundings in the Ebbinghaus illusion (Thelen & Watt, 2010). Based on their fixation patterns, it would be possible to determine whether they actually make visual comparisons between targets, or instead employ a less cognitively taxing response strategy. Secondly, eye-tracking could reveal whether differences between children's and adults' susceptibility to VIs can be explained by differences in their occulo-motor activity and test Piaget's theory of centration (e.g., whether younger children make fewer 'centrations' compared with older children and adults). Thirdly, eye-tracking would provide interesting insight into the role of top-down and bottom-up influences during the perception of VIs. For example, when inspecting VI stimuli, children may be increasingly drawn to salient features of images and pay less attention to context, thus exhibiting stronger bottom-up influences (Acik et al., 2010; Donnelly et al., 2007).

Conclusions

The present review has revealed that children's susceptibility to illusions develops over time, taking many years to reach adult-like maturity. Crucially, we observed that developmental trajectories differ between different illusions, response methods, and stimuli variations. The balance of evidence indicates that children decrease in their susceptibility to the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions as they get older, but increase in their susceptibility to the Ebbinghaus and Ponzo illusions with age. Extant literature has yet to pinpoint whether these changes occur due to the development of perceptual, neural, or cognitive mechanisms. However, it is vital to acknowledge that methodological variability may causally contribute to heterogeneity in findings across studies, and even yield opposing developmental trajectories for the same illusion. This is, perhaps, the key issue that future research ought to address in order to advance understanding of how children perceive and react to VIs. Future research is also necessary to explain why children are more or less susceptible than adults to specific illusions, and whether differences are simply an artefact of experimental design choices.

Chapter III

Thesis Continuity Statement

As indicated by the systematic review in Chapter II research on children's susceptibility to VIs is likely influenced by varying methodologies employed. Adjusting methods are more likely to reveal a diminishing effect with age (or no age-related effect), whereas forced choice paradigms are more likely to demonstrate an escalating effect with age. However, no previous research has directly investigated how methodological differences influence young children's VI susceptibility. By employing the Ebbinghaus illusion, we examined susceptibility using both methodologies in children aged 5 to 7 years of age and in young adults. This line of research will provide foundations for future studies investigating methodological differences in other illusions, as well as provide directions for the selection of methodology in future studies.

This Chapter has been written as an academic article. It reports the first out of two experiments intended for this article (second experiment investigates children's eye movements while investigating the Ebbinghaus illusion, which due to the time constraints will not be included in this thesis). It will be submitted to *Developmental Science* alongside other work on the illusion done outside of this PhD work.

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Abstract

Previous research has suggested that children exhibit diminished susceptibility to the Ebbinghaus illusion. However, the validity of this conclusion has been questioned due to methodological choices and potential response biases. The method of adjustment (MOA) method may be more likely to yield an effect showing decreasing magnitude with age, or no age differences. By contrast, the 2-way alternative forced-choice task (2AFC) tends to show that illusion susceptibility increases with age. Here, we utilised two commonly employed paradigms: MOA and 2AFC to investigate whether developmental trends would differ across these two methods. We hypothesised that younger children would display lower illusion susceptibility in the 2AFC condition, while no developmental differences would be detected in the MOA condition. Participants included 42 children between the ages of five and seven years, plus 39 young adults (*M*age = 20.1). They were tasked with either identifying the larger of two inner orange circles in the Ebbinghaus illusion (2AFC) or matching one of the inner orange circles to another (MOA). Results across both response methods revealed no differences in susceptibility between young children and adults. These collective findings suggest that susceptibility to the Ebbinghaus illusion is not affected by development nor differing methodologies.

Keywords: Ebbinghaus illusion, methodological differences, 2AFC, method of adjustment, response bias, development,

No Evidence for Reduced Susceptibility to the Ebbinghaus Illusion in Children Under the Age of Seven Years – A Method Comparison Study

Cognitive development and maturation contribute to comprehensive advancements across a wide range of psychological domains (Doherty et al., 2010). Consequently, observing superior performance by children in a psychological task may be considered unusual. Research on visual illusions (VIs) has indicated that children under approximately seven years of age may exhibit reduced sensitivity to geometrical VIs, such as the Ebbinghaus and Ponzo illusions (for a review, see Wincza et al., 2024). In other words, children respond more accurately than adults. This provides valuable insights into the progression of the human visual system. A more precise ability to discern size differences in an illusory context is linked to children's inability to perceive pictorial depth (Doherty et al., 2010) or to integrate various elements of a visual scene, indicating a diminished context integration ability (Kaldy & Kovacs, 2003). However, previous research has tended to overlook methodological differences in developmental investigations into susceptibility to VIs. In contrast to other studies in the field, here we compare children’s susceptibility to the Ebbinghaus illusion using two distinct methods. This approach will enable us to gain a deeper understanding of how different methodological paradigms might influence children’s responses. If children are less capable of integrating context (e.g., Kaldy & Kovacs, 2003), this effect should be universal regardless of the method used.

Developmental susceptibility trends related to the Ebbinghaus illusion have been a subject of extensive debate. Early studies, conducted by Coren and Porac (1978) and Weintraub (1979), reported that the magnitude of the illusion increases with age. Subsequent research has largely replicated these findings, consistently demonstrating that the illusion's magnitude is reduced in children aged 4 to 7 years (Bremner et al., 2016; Doherty et al., 2010; Imada et al., 2013; Kaldy & Kovacs, 2003; Kutuk et al., 2022; Mavridis et al., 2020; Schulze et al., 2022;

Thelen & Watt, 2010; Weintraub, 1979; Zanuttini, 1996). However, other studies have contested this finding. Investigations by Duemmler et al. (2008), Hadad (2018), and Hanish et al. (2001) indicated that similarly aged children and adults do not differ significantly in their susceptibility to the Ebbinghaus illusion. Finally, some authors have presented evidence that the illusion's magnitude decreases with age (Bondarko & Semenov, 2004; Grzeczkowski et al., 2017), underscoring the necessity for further research in this area. For a detailed insight into the developmental trends in susceptibility to the Ebbinghaus illusion, see Wincza and colleagues (2024).

Regarding the psychological explanation for reduced susceptibility to the Ebbinghaus illusion, Kaldy and Kovacs (2003) proposed that young children have not yet developed the ability to visually integrate different elements of the visual scene. Both children and adults are equally capable of discerning sizes when no misleading context (i.e., the surrounding circles) is provided (also see Doherty et al., 2010). This suggests that children's decreased susceptibility is not due to discerning abilities per se, but rather an inability to integrate the targets and the surroundings into a single, global picture. Alternatively, Doherty et al. (2010) suggest that the Ebbinghaus illusion is caused, at least partially, by subtle depth cues, which are not evident enough to cause an explicit perception of depth. They argue that children are not capable of perceiving pictorial depth to the same extent as adults, hence children under the age of seven years are less affected by the illusion.

A recent systematic review of developmental trends in susceptibility to VIs by Wincza et al. (2024) pointed out that inconsistencies may arise from methodological differences. The two main response methods in the field are the method of adjustment (MOA) and the two-way alternative forced-choice paradigm (2AFC). MOA requires the participant to increase or decrease one of the targets (e.g., one of the inner circles in the Ebbinghaus illusion) to match the other target which remains constant. The difference between the target and the comparison circle is then calculated. For a 2AFC task, the participant is required to indicate which of the two circles is larger. The size difference between the targets varies across trials. Participants' responses are either calculated as the grand score (sum of all the correct responses) or as a point of subjective equality (at what size difference the participant's response changes from target A to B).

Wincza et al. (2024) propose that the method of adjustment is more likely to produce results indicating a decreasing magnitude with age or no significant difference between children and adults. In contrast, the 2-way alternative forced-choice paradigm (2AFC) is argued to yield effects where susceptibility increases with age. These claims are informed by the fact that most studies using the 2AFC paradigm (Doherty et al., 2010; Imada et al., 2013; Kaldy & Kovacs, 2003; Kütük et al., 2023; Schulze et al., 2022; Thelen & Watt, 2004; and Zanuttini, 1996) found that the illusion's magnitude increases with age. Using, the method of adjustment (MOA), only Mavridis et al. (2020) corroborated these findings, while Hanish et al. (2001), Duemmler et al. (2008) found no differences between children and adults. Finally, using the MOA, Grzeczkowski et al. (2017) and Hadad (2018) reported that children's susceptibility decreases with age (for Hadad only when the contextual circles were bigger, as the children viewed the comparison circle in isolation, i.e., with no surrounding circles). These discrepancies suggest that methodological differences are a likely explanation for the differences in observed developmental trends for the Ebbinghaus illusion.

Differences in VI susceptibility between response methods may be linked to potential bias (i.e., a response bias; a systematic preference for one answer over another, Wetzel et al., 2016). Utilising a 2AFC paradigm developed by Philips et al. (2004), Wincza and colleagues (in preparation) found that children rely on a response bias. This was manifested by a relationship between low susceptibility to the illusion and low scores in a control condition designed to detect lapses in attention and bias. One advantage of this method is its limited number of trials (n = 24), making it more suitable for children, who typically have shorter attention spans (Betts et al., 2006). The reduced attention span has been suggested to relate to children's reduced susceptibility to the Ebbinghaus illusion (Wincza et al., 2024). However, in this paradigm, consistently selecting the circle with larger surroundings proves advantageous. In all instances, except for the control condition (4 trials) where the physically larger circle is presented in line with the illusory effect, the circle with larger surroundings is always larger. The authors observed that younger children, especially those under the age of seven years, exhibited a strong preference for indicating that the circle with larger surroundings is bigger, irrespective of its actual size (also see Thelen & Watt, 2010). This inclination towards the physically larger, and potentially more visually stimulating, aspect of the illusion suggest that children indeed rely on a bias. Further investigation into this bias could help to explain why children are less susceptible to the Ebbinghaus illusion.

The primary objective of this study is to examine developmental susceptibility to the Ebbinghaus illusion under two distinct methods: the method of adjustment and 2AFC. This research will help to understand whether previously observed developmental trends are due to methodological differences, or genuine reduced ability to integrate context (note, it was not our intention to compare the magnitudes of these two methods, as these were scored differently, but to investigate if these result in different statistical outcomes). To test this, a sample of children aged five to seven years, an age range in which susceptibility to the Ebbinghaus illusion starts shifting towards an adult-like perception (Wincza et al., 2024) and a sample of adults, was tested using both MOA and 2AFC paradigms. Also, as many previous studies investigated susceptibility differences between different age groups (e.g., Doherty et al., 2010), we aimed to conduct such analyses on top of analyses combining different children groups and adults. We anticipated that children would exhibit reduced susceptibility compared to adults when assessed through the 2AFC method, but not when employing the method of adjustment.

The findings of our study will help to resolve some of the discrepancies in the field, as well as will provide robust evidence concerning context sensitivity abilities in children.

Method

Participants

G*Power software (Faul et al., 2007) was used to perform an a priori power analysis to ascertain the necessary sample size required for a one-way ANOVA with four groups (5-year-olds, 6-year-olds, 7-year-olds, and a control group). Power (1- β) was specified as .80 and the significance level (α) was set to .05. The anticipated effect size was modelled on the results obtained by Wincza et al. (in preparation), who conducted a similar study on the Ebbinghaus illusion comparing children aged 5 to 11 years of age. Due to this, we anticipated a medium effect size of $f = 0.45$ (based on their smallest effect size of $d = 0.89$; d ranging from 0.89 to 1.92 for a between-subject difference between the youngest two groups of children and the older children and adults). For the frequentist parameters defined, a sample size of $N = 60$ for four groups is required to achieve a power of .80 at an alpha of .05. Hence, we aimed to recruit 60 participants.

In total, 71 participants were recruited across five groups (5-year-olds, 6-year-olds, 7-year-olds, and two control groups). The final sample is described after the exclusion criterion was applied for the 2AFC task, which resulted in the removal of some children (in each age group, one participant was removed due to a score of < 2 in the control condition, which indicates bias and/or misunderstanding of the task; Wincza et al. in preparation) and adult participants who completed only one part of the task. For the 2AFC task, 13 five-year-olds (females = 7), 13 six-year-olds (7 females), 11 seven-year-olds (females = 5), and 20 students from the University of East Anglia were recruited (age: $M = 20.63$, $SD = 3.26$, range = 18-29; females = 10). Students were recruited in exchange for SONA credits. For the MOA task, 15 five-year-olds (females = 9), 16 six-year-olds (9 females), 9 seven-year-olds (females = 3), and

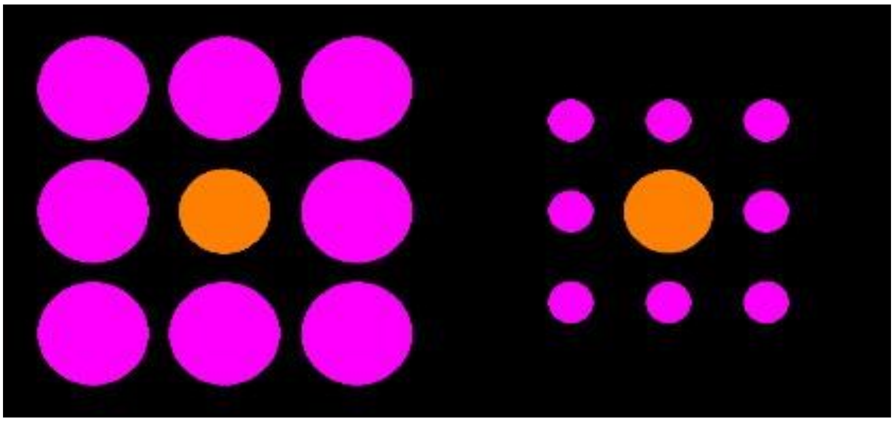
15 students from Lancaster University were recruited (age: *M* = 19.47, *SD* = 2.36, range = 18-27; females = 7). All participants were naïve to the study's purpose and the study received ethical approval from Lancaster University.

Materials

Participants were presented with the Ebbinghaus illusion (see Figure 1). The experiment was designed using E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). The large and small surroundings had a diameter of 1.62° and 0.62° of visual angles, respectively. The surroundings were placed at 0.38° of visual angle away from the inner circles. The targets varied in size from 1.05° to 1.53° visual angle, while the standard was held at 1.24° visual angle. The targets have been placed at an eccentricity of 2.48° of visual angle to the left and right of fixation cross, which appeared between the trials for 0.5 second. The illusion was counterbalanced by presenting reversed pictures. The order of presentation for all VIs was randomized. The experiment consisted of 24 trials, divided into six trial variations using a method developed by Philips et al. (2004). In one of these trial variatios, the context was designed to be helpful, resulting in no illusory effect. The other five trial variations were deliberately misleading. The non-manipulated parts of the stimuli were always maintained at a size of 100 pixels, and the manipulated parts varied in steps of 4 pixels (98 to 78 pixels) across all misleading conditions. The MOA task was designed using Unity3D® Gaming Engine, a game-developing software, and the Ebbinghaus illusion was modelled based on the works of Doherty et al. (2010) and Sperandio et al. (2016). Participants completed 16 trials. For half of the trials, the target circle started smaller or bigger (four times each) than the comparison circle within the smaller surroundings, and for the other half, it started larger or smaller (four times each) within the large surroundings. Additionally, eight trials were identical but reversed; the orientation of the illusion's layout switched. In the MOA task, susceptibility was measured as the difference between the target's size (participants' response) and the comparison circle that was held constant. The further the score would be from 0, the greater would be the susceptibility to the illusion (an overall score of 0, would indicate no susceptibility – the target and the comparison circle are identical in size). For the 2AFC task, the higher the score (more correct answers), the lower the susceptibility to the illusion.

Figure 1

The Ebbinghaus Illusion



Procedure

Data collection occurred during a research event organised by Lancaster's University BabyLab. Groups of four to seven children were invited with their parents to the lab and were given the opportunity to take part in psychological experiments, as well as other activities organised by the BabyLab. Each session lasted for about two hours and started by informing the parents about the study as well as obtaining their consent. Due to the nature of the event-like data collection process, not every child completed both tasks. During the 2AFC part of the experiment, the experimenter informed the children that they had to indicate which of the two orange circles was larger and, if they answered correctly for all of the trials, they would receive a prize. Then children sat in front of a computer and were shown 24 trials of the Ebbinghaus illusion. Children responded by either pointing to the circle of their choice or by saying either "left" or "right" and the experimenter noted down their answer. After this, the experimenter informed the children that they had answered all of these trials correctly and they received a book of their choice. In the MOA part of the experiment, children adjusted one of the two orange circles (while supervised) by pressing the corresponding key on the keyboard and were informed again, that if they do so correctly each time, they will receive a prize. When the child was happy that the two circles were identical, the experimenter pressed *enter*. The experimenter reminded the children throughout the task about what they have to do. Adult participants were psychology undergraduates tested in exchange for course credits. The order of methods was counterbalanced between participants and there was free play and activities between each part of the experiment. Lastly, the parents were debriefed and thanked for their cooperation.

Design and Analytic Plan

The study utilised a between-subject design. For the 2AFC task, scores from all trial types (except for the control trials) were added together to create a single score. The higher the score, the lower the susceptibility to the Ebbinghaus illusion. For the MOA, task, scores from all 16 trials were averaged within each participant. The value of 0 indicates no susceptibility at all. The further from zero (either positive or negative, although following the design, the susceptibility score would be a negative, as the constant size minus the perceived size, which would result in negative values) the greater levels of susceptibility are observed. The data were analysed using two one-way ANOVAs with the susceptibility score as the dependent variable, and group (5-year-olds vs. 6-year-olds vs. 7-year-olds vs. adults) as an independent variable, as well as a supplementary analysis between children and adults as an independent variable. This statistical approach is typical for studies in the field (e.g., Doherty et al., 2010). Alongside ANOVAs, these were also replicated using Bayesian ANOVAs, with a Bayes Factor of three and above, which were considered as evidence for the alternative hypothesis, while a Bayes Factor of less than 1/3, were considered as evidence pointing toward for the null hypothesis (Jarosz & Wiley, 2014). No priors were specified for the Bayesian analyses. Also, a correlation between the scores on both methods were performed. Outliers were altered using the method of winsorising which involves bringing the outlier's value to the closest value that is not considered to be an outlier (Dixon, 1960) – for example, if the outlier value was 17, but the closest non-outlier value was 15, 17 was reduced to 15. This method is known for its simplicity and robustness (Jose & Winkler, 2008). A common shortcoming of this method – applying an arbitrary cut-off point – was partly resolved in this study by selecting a widely-accepted cut-off of two standard deviations away from the mean.

Results

Outliers

No outliers were identified in the 2AFC task for any of the age groups. For the MOA task, one value was deemed to be an outlier (three standard deviations away from the mean). Using a simple, yet robust method of winsorising (Jose, & Winkler, 2008), their overall scores were brought to the closest value, which was not determined to be an outlier by RStudio. This was done to avoid the loss of any data points while acknowledging the extreme response, that might stem from individual differences. Overall, only one outlier was detected. In the group of adults, one total susceptibility value of 0.12 was decreased to 0.02.

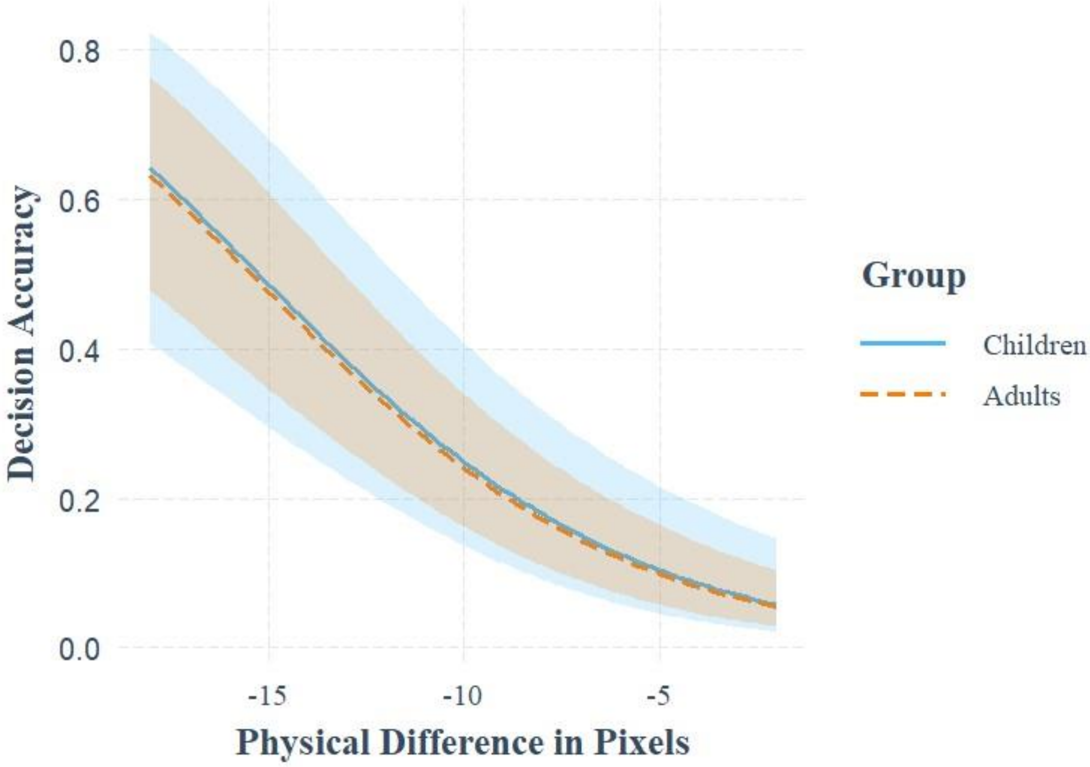
Repeated Measures ANOVA

For all ANOVAs, participants' susceptibility scores were entered into a one-way ANOVA with group as factor with four conditions: five-, six-, seven-year-olds, and adults.. The first one-way ANOVA (Levene's $p = .179$) indicated that on the 2AFC task, no significant age differences were observed when the independent variable was split based on age; $F(1, 55) = 0.02$, $p = .583$, $\eta p^2 = 0.04$, $BF_{10} = 0.18$. When, differences in susceptibility between children versus adults were measured using an independent samples t-test, the results, again, indicated no differences (Levene's *p*s > .149; Brown-Forsythe's $p = .786$); $t(55) = -0.19$, $p = .849$, $d = -0.05$, $BF_{10} = 0.28$. Similarly, for the MOA task, a one-way ANOVA (with Welch correction; Levene's $p < .001$) also indicated no significant differences between the three groups of children and adults; $F(3, 25.46) = 0.45$, $p = .718$, $\eta p^2 = 0.02$, BF10 = 0.13. Also, we observed no significant age differences between children and adults using an independent sample t-test (Levene's *p*s > .097; Brown-Forsythe's $p < .001$, hence a Welch correction was applied); $t(53) = -0.66$, $p = .641$, $d = -0.15$, $BF_{10} = 0.35$. For children who took part in both studies, no correlations were observed between their scores on the 2AFC and MOA tasks, either when assessed as a whole group, or individual age groups: *p*s > .305 ($n = 38$); all $BF_{10} < 0.59$. See Figure 2 (2AFC) and Figure 3 (MOA) below for the visualisation of the data for both methods.

Furthermore, participants' susceptibility scores in the control condition were entered into a one-way ANOVA with age group as a factor with four conditions: five-, six-, seven-year-olds, and adults, similarly to Doherty et al. (2010). There was a gradual increase in accuracy in this condition, with five-year-olds scoring lowest ($M = 3.64$, $SD = 0.50$ - % correct = 91%), followed by six- and seven-year-olds ($M = 3.83$, $SD = 0.39$, % correct = 96% and $M = 3.91$, SD = 0.30, % correct = 98% respectively), and adults ($M = 3.95$, $SD = 0.22$, % correct = 99%). Doherty and colleagues (2010) observed large differences between children and adults and a moderate-to-strong negative correlation between the scores in the control condition (helpful as it is referred to in their study) and the overall susceptibility scores. On the contrary, here we observed no main effect of group when assessed independently (Levene's p < .001, hence Welch correction was applied): $F(3, 23.91) = 1.61$, $p = .213$, $\eta p^2 = 0.11$, $BF_{10} = 0.18$. Also, an independent samples t-test between children and adults showed no significant differences: $t(55) = 1.65$, $p = .104$, $d = 0.46$, $BF_{10} = 0.85$. Furthermore, we did not observe such correlation either between age and the scores in the control condition; $r(57) = .244$, $p = .067$, $BF_{10} = 0.85$, nor between the scores in the control condition and over all susceptibility scores: $r(57) = -.195$, $p = .146$, $BF_{10} = 0.46$.

Figure 2

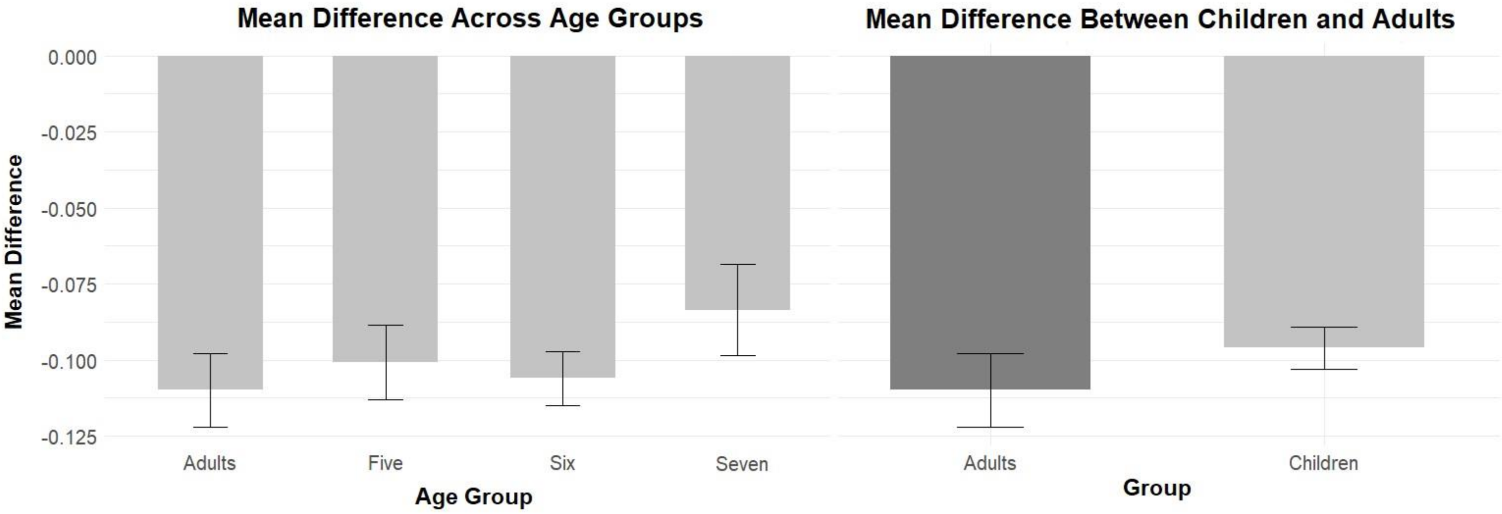
Accuracy Across Different Trial Types For the 2AFC Task



Note. Values on the Y-axis indicate the mean susceptibility score across conditions. A score of 0 indicates full susceptibility.

Figure 3

Mean Differences Across Age Groups for the MOA Task



Note. The further the difference is from zero, the greater the susceptibility to the illusion. The bars represent the standard error for each group.

Discussion

Contrary to our initial hypothesis, children did not demonstrate reduced susceptibility to the Ebbinghaus illusion when assessed using the 2AFC method. However, the absence of significant group differences for the MOA task supported our hypothesis that children would not differ significantly in susceptibility from adults. These findings are at odds with numerous studies in the field (e.g., Doherty et al., 2010), which have shown that children below the age of seven years are typically less susceptible to the Ebbinghaus illusion compared to older children and adults. From our findings, we conclude that context integration and pictorial depth perception – both of which have been proposed to be linked with reduced susceptibility to the Ebbinghaus illusion in younger children (Kaldy & Kovacs, 2003; Doherty et al., 2010) – develop before the age of five years.

Compared to earlier research in the field, such as Kaldy and Kovacs (2003) and Schulze et al. (2022), this study did not include any four-year-olds. These earlier studies suggested that susceptibility to the Ebbinghaus illusion diminishes at the age of four. However, other studies, like those by Kutuk et al. (2023) and Mavridis et al. (2020), still observed an increasing trend with age (despite testing five-year-olds and older children), while in some cases, only children over the age of seven began to exhibit adult-like performance (e.g., Doherty et al., 2010). This implies that the ability to visually integrate different elements develops around the age of five, or possibly even earlier, as indicated by nearly identical scores between children and adults across trial conditions in the present study. This is further supported by the Bayes Factors which have largely provided (or closely to) evidence if favour of the null hypothesis. Also, as expected as the illusion's magnitude weakened, the response accuracy improved suggesting that as the difference between the two target circles increased participants' accuracy to detect size difference increased. The earlier onset of this ability is perhaps unsurprising, as Doherty and colleagues (2010) argue that the capacity to integrate context is a key milestone in cognitive development. A prolonged inability to visually integrate context during childhood would likely have negative effects on learning and developmental progress, therefore it should develop relatively soon. Therefore, it is plausible that this ability develops earlier than previously believed, however, more research is needed to confirm that.

In developmental research focusing on the Ebbinghaus illusion, Thelen and Watt (2010) observed that children below the age of six appeared to be less influenced by the illusory context. Upon closer examination of the data, it was discovered that younger children tended to exhibit perseveration on one type of answer, showing a preference for larger surroundings. When this bias was controlled for, children no longer demonstrated signs of reduced susceptibility to the Ebbinghaus illusion. In light of the findings from Thelen and Watt's study, and ongoing work by Wincza and colleagues (in preparation), we noted significantly less reliance on biases in our own study. Most of the children in our study did not exhibit failures in the control condition. This contradicts previous findings by Wincza and colleagues (in preparation), who reported exclusions as high as 26% and 30%, compared to less than 5% in this study. Consequently, we did not replicate this previously observed pattern, which had been frequently replicated using the same method in prior studies (e.g., Doherty et al., 2010; Imada et al., 2013; Schulze et al., 2022).

Furthermore, the performance in the control condition contradicts the findings of Doherty and colleagues (2010). In their study, four- to six-year-olds performed at chance level (50%) in an identical control condition to the one used here, whereas in this study, five- and six-year-olds achieved scores of 91% and 96%, respectively. This suggests that the children are employing a specific bias during the task – perhaps selecting the surrounded circle with larger outer circles, as this occupies a greater proportion of their visual field, regardless of the size of the targest. In the design of this study, such a bias would lead to high scores in the experimental condition but lower scores in the control condition. Although it is unlikely that the children are consciously aware of this, it indicates that they may be relying on a response bias in situations of uncertainty, as their scores are still not at ceiling level (e.g., Doherty et al., 2010). Alternatively, it is possible that the children are not fully attending to the task, either by not engaging with it properly or by confusing the selection of the larger inner circle with the selection of the overall configuration (small versus large surrounds).

We speculate that this discrepancy may have arisen due to two potential reasons. Firstly, although such data was not collected (hence these speculations should be treated cautiously), the children recruited for this study largely came from better socio-economic backgrounds than children tested by Wincza and colleagues (in preparation), often being children of other academics at Lancaster University. Most of these children are also frequent visitors to the lab, making them experienced participants. It is, therefore, likely that the low number of excluded children was due to the fact that these children were better at focusing on the task than their peers. Previous research has highlighted negative correlations between fluid intelligence (as measured by Raven's matrices) and total susceptibility scores (Doherty et al. 2010; Wincza et al. in preparation) as well as positive correlations between the scores in the helpful (control) condition and fluid intelligence (Wincza et al. in preparation) are linked to the Ebbinghaus illusion susceptibility. In light of these findings, it is reasonable to assume that if the children from this study were tested on the Raven's matrices, they would have higher scores than the children in the studies by Doherty et al. and Wincza et al. However, these speculations need to be treated cautiously, and such links need to be validated in future research. Alternatively, contrary to the study by Wincza et al. (in preparation), the children were told that if they did well, they would receive a prize. This could have led to greater levels of intrinsic motivation, resulting in staying on task for longer, thus perceiving the illusion to a stronger extent. This is further supported by generally higher levels of susceptibility compared to studies conducted by Doherty et al. (2010) and Wincza et al., (in preparation).

The lack of control for fluid intelligence represents the study's most significant limitation. Future investigations should delve deeper into the influence of attention and fluid intelligence on susceptibility to VIs such as the Ebbinghaus illusion, as well as others like the Ponzo illusion. Secondly, future studies should directly examine children who exhibit a bias-driven approach (low scores in the control condition) and compare them with perception-driven children (high scores in the control condition). Such a comparison would yield greater insight into the roles of biases and bias utilisation among children. This approach could provide valuable information regarding the interplay between cognitive strategies and perceptual abilities in children's responses to VIs.

Conclusion

Across two methods (MOA, and 2AFC after Phillips et al. 2004), we found no evidence for developmental differences in susceptibility to the Ebbinghaus illusion after the age of five years. Our results indicate that five-, six-, and seven-year-olds are equally influenced by the illusory context as adults, meaning they incorporate the illusory-inducing elements comparably. These findings underscore the necessity to reevaluate previous studies on susceptibility to visual illusions (VIs) in children, as these may also be influenced by methodological disparities and biases. Moreover, we demonstrate that claims suggesting that context integration and pictorial depth perception reach an adult-like level of performance after the age of seven are likely to be inaccurate.

Chapter IV

Thesis Continuity Statement

Somewhat surprisingly, in Chapter III we did not find the expected methodological differences in children, indicating that children's susceptibility to the Ebbinghaus illusion can be adequately measured using both the method of adjustment and 2 way-alternative forced-choice methods. However, it is still pressing to investigate these differences in adults, as such research is lacking. Furthermore, as the factor of sex was identified as a potential confounding variable in Chapter II, it is important to investigate whether methodological differences are affected by sex differences. It is especially important as many studies in the field have an uneven sex ratio, something that is often caused by the higher prevalence of females in psychology courses, from which vast numbers of participants are usually recruited. Together with Chapter III, Chapter V will provide a compelling insight into methodological differences in childhood and early adulthood. Initially, the study aimed to investigate methodological differences using three VIs; the Ebbinghaus, Ponzo, and Muller-Lyer, but regrettably, due to an internal issue, the findings regarding the Ponzo illusion are not included in the following experiment.

This Chapter has been written as an academic article. The aim is to submit this article to *Perception*.

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Abstract

Contrasting outcomes in developmental research on visual illusions (VIs) susceptibility may be attributed to methodological differences, however, such research in adult samples is lacking. Biological sex has also been identified as a factor that may contribute to VI susceptibility but is rarely accounted for in empirical studies. This study aimed to bridge the research gap by investigating how methodological and sex differences influence adults' susceptibility to VIs. Across three experiments, we utilised two VIs (Ebbinghaus and Muller-Lyer) and three different methods of studying VIs susceptibility; 2 way-alternative forced-choice paradigm (2AFC), method of adjustment (MOA), and 2AFC without randomisation. Experiment 1 with 80 undergraduate students showed that males have reduced susceptibility to the Ebbinghaus illusion using a 2AFC task after Phillips et al. (2004), but also spent increased time viewing the illusions. Experiments 2 and 3 with 120 undergraduate students showed no sex differences in terms of VIs susceptibility and no relationships with viewing time were detected. The points of subjective equality differed substantially between MOA and 2AFC without randomisation, with the former producing larger susceptibility scores, but only for the Muller-Lyer illusion. Our results illustrate that, despite certain overlaps, different methods yield varying results, differing not only in outcome but also in magnitude. Across two VIs and three different methods, sex was shown to only affect susceptibility to the Ebbinghaus illusion in one specific method, suggesting that overall females and males perceive and respond to VIs similarly. Collectively, these results indicate that different methods may require a different set of decisional criteria, which can influence the appearance of VI susceptibility. This finding underscores the necessity for greater methodological consideration in future studies.

Keywords: Ebbinghaus illusion, Muller-Lyer illusion, visual illusions, method of adjustment, two-alternative forced choice, methodological differences, sex differences,

Susceptibility to Visual Illusions Across Methods and Sexes

Visual illusions (VIs) are phenomena in which perceived object properties, such as colour or size, differ from their actual physical properties, thus providing a unique tool for studying human visual perception. Exploring VIs has revealed insights into various perceptual abilities, including depth perception (Gregory, 1963) and context integration (Kaldy & Kovacs, 2003), as well as their impact on mental health conditions like schizophrenia (for review see; Costa et al., 2023; King et al., 2017) and neurodevelopmental conditions like autism (for review see Gori et al., 2016). Sex differences have also been found when investigating VIs susceptibility (e.g., Miller, 2001), although compelling evidence of their existence (or lack thereof) is lacking. The study of this phenomenon has been primarily conducted using either the method of adjustment (MOA) or the two-alternative forced-choice (2AFC) paradigms. In MOA, participants adjust one of the targets, such as an inner circle in the Ebbinghaus illusion, while keeping the other constant until they match. In a 2AFC task, participants must select the larger of two targets, with the difference between targets presented in equal intervals (from here onwards referred to as 2AFC without randomisation) or with the intervals being randomised within the experiment (e.g., 2AFC after Phillips et al., 2004). However, previous research has largely neglected differences between these methods, including variability in exposure time, when interpreting results concerning VI susceptibility in adult samples. This study aims to bridge the research gap by investigating how VI susceptibility is influenced by biological sex and response method.

Although widely used in VIs research, response methods themselves have received limited attention. This is particularly significant because previous research has indicated that the choice of method could contribute to discrepancies within the field. In their review, Wincza and colleagues (2024) highlighted that developmental research on VIs often yields contradictory findings when employing two distinct methods. The MOA typically produces non-significant differences between children and adults or indicates increased illusion magnitudes in children, while the 2AFC method often shows that children are less susceptible to VIs than adults. These observations may suggest that different cognitive abilities come into play for each method. The 2AFC method may be more susceptible to cognitive biases, such as employing a response bias rather than relying on visual discrimination, which could lead to systematic selection of stimuli regardless of their physical properties. For example, in situations of uncertainty, the participant might guide their selection based on non-visual aspects, such as their reasoning behind how an illusion work, thus in the case of the Ebbinghaus illusion for example, always selecting only one set of surrounding circles (either small or large). This has already been observed in previous research with children (Wincza et al., in prep). The MOA is a more cognitively demanding method as it requires participants to actively manipulate stimulus size, potentially favouring individuals with better task focus and attention.

The only notable exception where difference between methods was compared, is a study conducted by Cretenoud et al. (2021), where susceptibility scores were compared between MOA and 2AFC in a sample of 20 university students. The findings revealed no significant differences in susceptibility scores between the two methods. However, an interesting observation emerged when examining participants' performance on the outward and inward versions of the Muller-Lyer illusion. When the line of interest pointed inward, participants displayed slightly higher susceptibility using the MOA method. Conversely, when the line pointed outward, participants exhibited greater susceptibility using the 2AFC method. However, both differences failed to reach significance. This suggests that specific decisional biases may still influence individuals' responses to visual illusion tasks, underscoring the complexity of factors influencing susceptibility or that the different demands of the different methodologies may affect participants' susceptibility.

Cretenoud and colleagues' (2021) suggest that the high number of trials often required by 2AFC tasks may contribute to tiredness compared to MOA tasks, which have traditionally many fewer trials. Wincza and colleagues (2024) argue that fatigue and boredom can give rise to the development of "strategies" or certain preferences in children. For example, Thelen and Watt (2004) showed that when controlling for children’s preferences for choosing the circle with larger surroundings, their superior ability to detect size differences diminishes. These strategies help participants handle the task more conveniently, reducing cognitive demands. Barch and colleagues (2012) observed that lapses in attention during VI tasks can confound results. In the case of patients with schizophrenia, their susceptibility to VIs appeared to be diminished, but when controlling for lapses in attention, the effect became non-significant (Barch et al. 2012).

There is conflicting evidence regarding sex-related differences in susceptibility to VIs, with some studies suggesting that VIs are a unisex phenomenon while others suggest that males have reduced susceptibility. Porac and colleagues (1979) conducted a comprehensive study that involved testing participants on 45 different illusion variants, including well-known illusions like the Ebbinghaus, Ponzo, and Muller-Lyer. Their findings indicated no significant differences in susceptibility between males and females. Subsequent studies supported these results by demonstrating that sex differences do not influence susceptibility to the Baldwin illusion (Holland et al., 1990) or the Muller-Lyer illusion (Dewar, 1967). However, Miller (2001) presented contrasting findings, suggesting that males exhibit greater resistance to the Ponzo illusion compared to females. This led to the conclusion that females tend to be more field-dependent, meaning they rely more on contextual information in their perception, thereby increasing their susceptibility to illusions. Moreover, a large-scale study with an average of approximately 2000 participants per illusion revealed that males display lower susceptibility to the Poggendorff, Ponzo, and Muller-Lyer illusions, with the Poggendorff illusion showing the strongest effect on females and the Muller-Lyer illusion displaying the least effect (McGraw, n.d.). Philips and colleagues (2004) also demonstrated that the Ebbinghaus illusion is of reduced magnitude in males, indicating that females are more sensitive to contextual cues than males. More recently, Shaqiri et al. (2018) found that females are more susceptible to the Ponzo illusion than males, while no significant differences were observed for the Ebbinghaus, Muller-Lyer, and Tilt illusions, as well as a modified version of the Ponzo illusion. These collective findings suggest potential differences between females and males concerning perception and susceptibility to VIs. However, previous research has not provided an answer to whether sex differences in susceptibility to VIs are linked to reaction times, and whether they are stable across different methods.

Similarly, research on time exposure and VIs susceptibility is scarce. A notable exception is a large-scale study involving over 550 participants which suggests that prolonged exposure to the Ebbinghaus illusion diminishes its magnitude – longer exposure allows for better focus on the task-relevant areas (Bressan & Kramer, 2021). However, recent studies into cross-cultural differences between Himba and French participants indicated that differences in susceptibility were not driven by exposure to the illusion (Caparos & Boissin, 2024). It is, therefore, possible that the effects of time exposure on susceptibility to VIs may differ between females and males, and in general result in a reduced magnitude of the experienced illusion.

The study had two objectives. Firstly, we were interested in whether the different methods would produce similar trends in VIs magnitude across sexes, as well as whether points of subjective equality (PSEs) would be comparable across methods. Using three different methods of investigating VIs (MOA, 2AFC, and 2AFC without randomisation), we investigated methodological differences in susceptibility to two well-known VIs (the Ebbinghaus and Muller-Lyer illusions). Furthermore, we investigated the reaction times in responding to the task, in two samples of participants (within- and between-designs). We hypothesised that males would be less susceptible than females and that these differences would be constant across all three methods – and where PSEs can be calculated, these would not differ across methods (MOA and 2AFC without randomisation). Secondly, we aimed to investigate if correlations exist between participants' RTs and their susceptibility scores. Here, we hypothesised that longer exposure would reduce participants' susceptibility to VIs. Our findings will provide compelling evidence for the existence (or lack thereof) of susceptibility differences between males and females, and whether these differences are contingent upon the method used. Furthermore, it will provide insight into whether different methodologies yield comparable illusions magnitudes.

Experiment 1 – Two-Alternative Forced-Choice Paradigm After Phillips et al. (2004)

Method

Participants

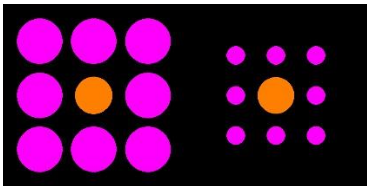
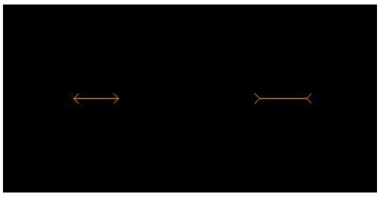
A total of 80 participants (40 females) were recruited through the SONA systems at the University of East Anglia in the United Kingdom. The majority of participants were psychology undergraduates (n = 52) who participated in exchange for credits, while the remaining participants were renumerated with money. The age of the participants did not show significant differences between females (M = 20.53, SD = 3.13, range 18-31) and males (M = 21.88, SD = 3.03, range 18-34); $t(78) = 1.96$, p = .054. The participants mainly consisted of individuals of British origin (n = 54) or Polish origin (n = 15), with other minorities represented such as Iranian, Malaysian, New Zealander, Russian, Slovak, Swiss, Turkish, or Vietnamese participants. In order to be eligible to take part in the study, participants had to self-report if they had normal or corrected-to-normal vision. The study was ethically approved by the University of East Anglia.

Materials

Participants were presented with two VIs: the Ebbinghaus and Müller-Lyer illusions. The experiment was designed using E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). The pictures displaying the Ebbinghaus illusion had dimensions of 1000 pixels in width and 500 pixels in height. As for the Müller-Lyer illusion, its dimensions were 800x400 pixels. During the task, the target parts of the stimuli (manipulated portions of the VI) were consistently presented in orange, while the context remained constant and was always in purple (this applies only to the Ebbinghaus illusion). The non-manipulated parts of the stimuli were always maintained at a size of 100 pixels. In the Ebbinghaus illusion, the large and small surroundings had diameters of 150 and 50 pixels, respectively. The arrowheads in the Müller-Lyer illusion were set at a 45-degree angle. Both VIs were counterbalanced by presenting reversed pictures. The order of presentation for all VIs was randomized. The experiment consisted of 24 trials per illusion, divided into six trial types, using a method developed by Philips et al. (2004). In one of these trial types, the context was designed to be helpful, resulting in no illusory effect (the perceived as larger/longer was in fact larger or longer by 2 or 4 pixels for the Ebbinghaus and Muller-Lyer illusions, respectively). The other five trial-type were deliberately misleading. Each misleading trial type differed in size in steps of 4 pixels, starting from 98 (hardest condition) to 78 pixels (easiest condition) for the Ebbinghaus illusion. For the Muller-Lyer illusion, it varied in steps of 8 pixels starting from 96 pixels.

Table 1

The illusions used in experiment 1 are presented below, with an explanation of their illusory effect and an example of the stimuli used.

Illusion	Effect	Picture
The Ebbinghaus illusion	In this illusion, the orange circle surrounded by smaller circles is usually perceived as larger than the other one.	
The Muller-Lyer illusion	Traditionally, the line with arrowheads pointing outwards is perceived as shorter than the other line.	

Procedure

Participants were tested at the psychology labs on the University of East Anglia's campus. Upon entering the laboratory, each participant was greeted by the researcher and handed an information sheet. Written consent was obtained from each participant before commencing the experiment. Depending on the number of sign-ups, participants were tested either individually or in small groups, and they were provided with private cubicles to complete the experiment. Once seated in front of the computer, participants were instructed to maintain an upright position and refrain from leaning forward, backward, or sideways to ensure consistent viewing conditions throughout the experiment. The distance between the participant's face and the screen was approximately 63cm, which was ensured by asking them to sit with their stomachs touching the edge of the desk. Before starting the visual task, participants were informed that they would be presented with a battery of VIs. They were specifically instructed not to try to 'see through the illusions' but to trust their initial impressions and respond as quickly and accurately as possible. In case of uncertainty, participants were encouraged to make their best guess. Prior to completing the visual task, participants also provided information about their age and sex. Upon completing the task, participants received a debrief form and had the opportunity to ask any questions about the experiment. They were thanked for their participation in the study and received their reward, which could be either monetary or credits, as applicable.

Analytic Plan

Firstly, the normality of the dataset was assessed. Additionally, outliers were handled using the common technique of 'winsorising' (further details provided below). To detect differences in susceptibility scores and response times (RTs – both dependent variables for each ANOVA) between females and males (independent variable) two two-way mixed design ANOVAs were conducted. RTs were averaged within participants. Susceptibility was measured as follows: each trial contained a correct answer since the targets always differed in size. A correct answer earned a point, while an incorrect answer received none. Thus, a higher score indicated lower susceptibility to the illusion. Any group differences were followed up with planned comparisons using independent t-tests and paired samples t-tests. Additionally, correlations were performed to investigate the relationships between different illusions among females and males, as well as their RTs. Effect sizes were measured using Cohen's *d*. Corresponding Bayes Factors were calculated separately for each analysis, with no specific prior specified. A Bayes Factor of three and above, which will be considered as evidence for the alternative hypothesis, while a Bayes Factor of less than 1/3, will be considered as evidence pointing toward for the null hypothesis (Jarosz & Wiley, 2014).

Results

Outliers

Several outliers were detected across variables, and screening for outliers was conducted independently for each group and for each VI. However, instead of removing the outliers from the dataset, a common technique known as 'winsorising' was employed. This approach involves adjusting the outlier's value to the nearest non-outlier value (Dixon, 1960), known for its simplicity and robustness (Jose & Winkler, 2008). This was done to acknowledge the extreme value which might reflect individual differences, as well as to avoid removing any data points. Applying this method, two average RTs (all male) for the Ebbinghaus illusion were 'winsorised' down from 7.3 and 3.9 seconds to 3.1 seconds. Additionally, three outliers were identified for the Muller-Lyer illusion (all male), and their values were 'winsorized' down from 4.8, 3.9, and 2.9 to 2.4 seconds. Regarding the susceptibility scores, outliers were observed exclusively for the Muller-Lyer illusion. Four values were 'winsorized' down from 16 and 15 to 14, while four values were 'winsorized up' from 6, 7, 8, and 10 to 11 for males. For females, one value was 'winsorized' down from 20 to 16, and three values were 'winsorized up' from 6 and 7 to 8.

Normality of the Data Set

The normality of the dataset was assessed using the classical normality test, Shapiro-Wilk. The results indicated that all variables were not normally distributed ($p < .001$). However, the *F*-tests intended to be carried out here are largely immune to non-normal distribution (Blanca et al., 2017; Khan & Rayner, 2003). It is worth noting that Shapiro-Wilk is known for yielding unreliable results for large samples ($n > 50$; Royston, 1982; Razali & Wah, 2011; Kim, 2013). As the sample size increases, the standard errors become smaller, which can cause z-tests to reject the normal distribution assumption in large samples that, in reality, do not significantly differ from a normal distribution (Kim, 2013). To validate the assumptions of normality, visual examinations of histograms and Q-Q plots were performed (Kim, 2013). The data met the assumptions of normal distribution, which aligns with the central limit theorem that assumes large data sets ($n > 30$) follow a normal distribution (Kwak & Kim, 2017).

Two-Way Mixed-Design ANOVAs

Susceptibility Score Analysis.

Levene's tests of equality of variances have been violated for the susceptibility score to the Muller-Lyer illusion ($p = .043$). Participants' susceptibility scores were entered into a two-way (sex: male, female) x (illusion: Ebbinghaus, Muller-Lyer) mixed ANOVA. The analysis revealed a significant main effect of illusion; $F(1, 78) = 17.6$, $p < .001$, $\eta p^2 = 0.18$, $BF_{10} = 543.28$, as well as a main effect of sex; $F(1, 78) = 7.9$, $p = .006$, $\eta p^2 = 0.09$, $BF_{10} = 3.49$. Also, we observed an illusion x sex interaction; $F(1, 78) = 4.57$, $p = .036$, $\eta p^2 = 0.06$; $BF_{10} = 4731.12$. See Figure 1 for the visualisation of the data. Planned comparisons indicated that males ($M = 11.7$, $SD = 4.12$) were significantly less susceptible to the Ebbinghaus illusion than females ($M = 9.28$, $SD = 3.81$), $t(78) = 2.74$, $p = .008$, $d = 0.61$, $BF_{10} = 5.52$. The difference between females' ($M = 12.2$, $SD = 2.1$) and males' ($M = 12.55$, $SD = 1.09$) performance on the Muller-Lyer illusion was non-significant, $p = .560$, $BF_{10} = 0.40$. As shown, by a paired-samples t-test, participants were less susceptible to the Muller-Lyer illusion ($M = 12.43$, $SD = 1.81$) than the Ebbinghaus illusion ($M = 10.49$, $SD = 4.13$); $t(79) = -4.11$, $p < .001$, $d = -0.46$, $BF_{10} = 202.16$. This was however not observed for males (Ebbinghaus – $M = 11.70$, $SD = 4.12$, and Muller-Lyer – $M = 12.65$, $SD = 1.44$; $t(39) =$, $p = .175$, $d = -0.22$, $BF_{10} = 0.41$) and but only for females (Ebbinghaus – $M = 9.28$, $SD = 3.81$, and Muller-Lyer – $M = 12.20$, $SD = 2.10$; $t(39) = -4.76$, $p < .001$, $d = -0.75$, $BF_{10} = 781.20$).

Reaction Times Analysis.

Levene's tests of equality of variances have been violated for the RTs for the Ebbinghaus illusion ($p < .001$). However, as noted by Field (2018), if the groups are large, the violation of

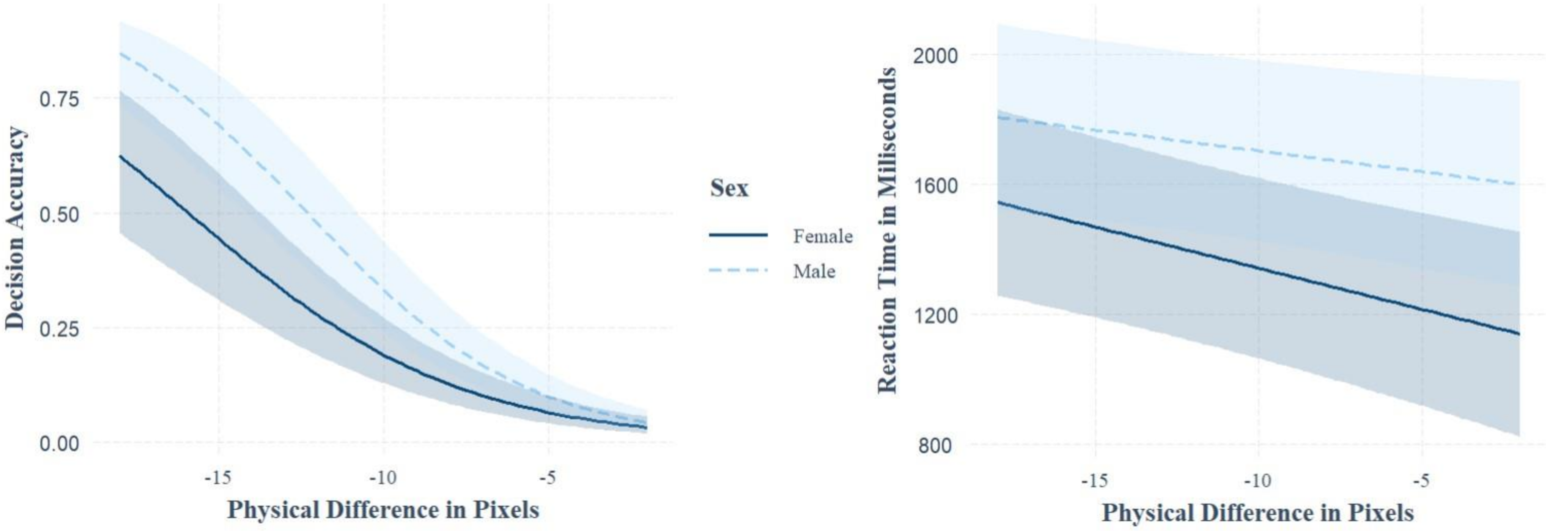
Levene's test is not considered to be of significant concern. Participants' susceptibility scores were entered into a two-way (sex: male, female) x (RTs to VIs: Ebbinghaus, Muller-Lyer) mixed ANOVA. The analysis revealed no main effect of RT to VIs; $F(1, 78) = 0.14$, $p = .714$, $\eta p^2 < 0.01$, $BF_{10} = 0.18$, as well as no main effect of sex; $F(1, 78) = 1.40$, $p = .241$, $\eta p^2 = 0.02$, $BF_{10} = 0.59$. Finally, there was no interaction sex x RTs; $F(1, 78) = 2.36$, $p = .129$, $\eta p^2 = 0.03$, $BF_{10} = 0.07$. See Figure 2 for the visualisation of the data.

Correlations

We assessed correlations between susceptibility scores and RTs for both groups combined. Pearson's correlations indicated significant positive correlations between susceptibility scores and RTs for the Ebbinghaus illusions; $r(78) = .361$, $p < .001$, $BF_{10} = 28.80$, but not for the Muller-Lyer illusion; $r(78) = .036$, $p = .749$, $BF_{10} = 0.16$. However, these correlations were stronger for males than females (as indicated by Bayes Factors), when assessed independently. For the Ebbinghaus illusion, the correlation rose to $r(78) = .472$, $p = .002$, $BF_{10} = 18.71$, but not to the Muller-Lyer illusion; $r(78) = .014$, $p = .93$, $BF_{10} = 0.21$. None of the correlations for females approached significance (ps $> .659$; all $BF_{10} < 0.22$). Correlations between the Ebbinghaus and Muller-Lyer illusions did not reach significance ($p = .446$; $BF_{10} = 0.39$).

Figure 1

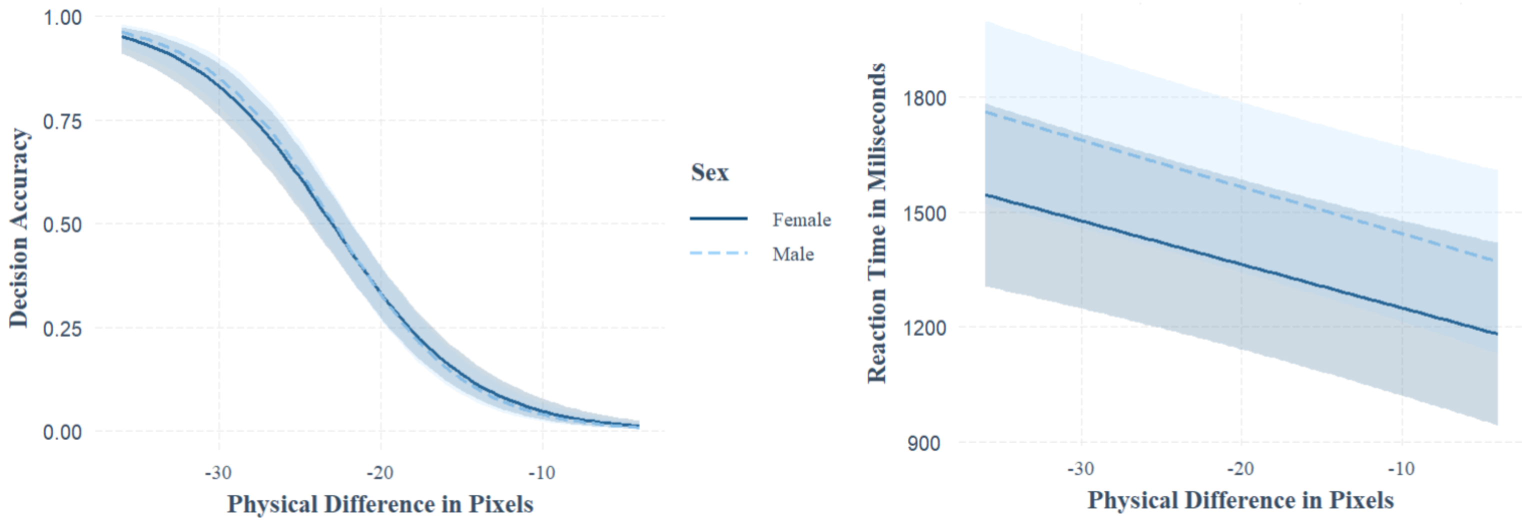
Responses and RTs Across Different Trial Types for the Ebbinghaus Illusion



Note. The larger the physical difference between the target and the comparison circle, the easier the experimental condition.

Figure 2

Responses Across Different Conditions for the Muller-Lyer Illusion



Note. The larger the physical difference between the target and the comparison line, the easier the experimental condition.

Discussion

Experiment 1 confirmed the hypothesis that males would be less susceptible to the Ebbinghaus illusion than females, thus replicating the findings of Phillips et al. (2004).

Although, a positive and moderate correlation between accuracy and RT for the Ebbinghaus illusion was observed for males, partially confirming our second hypothesis, the differences in RTs between females and males were not significant. It therefore appears that increased exposure to the Ebbinghaus reduces its susceptibility, but only for males, suggesting a speed-accuracy trade-off. No sex differences were observed for the Muller-Lyer illusion. In order to test the robustness of the observed sex differences, an additional set of studies using different methods and a different sample was conducted.

Experiment 2 – Method of Adjustment

Introduction

One of the most commonly used methods in the field of VI research is MOA (Wincza et al., 2024). Therefore, we intended to replicate the findings of Experiment 1 using this method. Doing so will allow a better understanding of whether these two different methods will yield comparable sex differences. By doing so, we will not only provide stronger evidence for such sex differences, but most importantly, we will show whether differing methods produce comparable results. This is of particular importance, as most previous studies do not provide a rationale for their choice of method.

Method

Participants

For Experiments 2 and 3, a different set of participants was recruited. A total of 120 participants took part in this study; 60 females (*M*age = 19.5, *SD* = 2.19, range = 18 – 29) and 60 males (*M*age = 22.28, *SD* = 3.58, range = 18 – 30), with males being significantly older than females [$t(118) = 5.14$, $p < .001$] – this was not considered problematic as both groups can be classified as young adults. Of this sample, 24 males and 41 females completed the experiment online. The age of the participants did not differ significantly compared to the sample from Experiment 1 mentioned above; $t(198) = -0.69$, $p = .491$. The majority of the participants (n =

102) were recruited via a research participation system in exchange for credits from Lancaster University in the United Kingdom, while the remaining participants were recruited via opportunity sampling. Among them, 68 were psychology undergraduates, and 69 identified as British, while 32 were of Polish origin. Additionally, there were participants from various other nationalities, including Italian, Indian, Malaysian, Lithuanian, Spanish, Dutch, and Chinese. Similarly, as in Experiment 1, to be eligible to take part, normal or corrected-to-normal vision was required. The study received ethical approval from Lancaster University.

Apparatus and Materials

The experiment was designed using Unity3D® Gaming Engine, a game-developing software. All VIs were modeled based on the works of Doherty et al. (2010) and Sperandio et al. (2016). Participants were instructed to complete a task that included the Ebbinghaus and Muller-Lyer illusions. These illusions were identical in appearance to the ones mentioned above, with the exception that the lines in the Muller-Lyer illusions were wider. The MOA was employed for this task. In the Ebbinghaus illusion, participants completed 16 trials. For a quarter of the trials (two reversed – illusion's layout rotated), the target circle started smaller than the comparison circle, and for another quarter (two reversed) it started larger within the large surroundings. Additionally, eight trials were identical but reversed – the circles identically varied in the smaller surroundings as within the larger surroundings. For the Muller-Lyer, in a quarter of the trials, the target line started shorter than the comparison line, and the other quarter, it started longer when the arrowheads pointing outwards. Additionally, eight trials were identical but within the arrowheads pointing inwards.

Procedure

The order of Experiments 2 and 3 was counterbalanced. When testing participants in person, the experiment was conducted on a 15-inch HP Omen laptop with the brightness level set to maximum. However, due to COVID-19 restrictions, some of the testing had to be done online via Microsoft Teams. This was not considered problematic, as previous studies across a range of domains indicate that online studies yield comparable results to in-person studies (Bogdan et al., 2023; Buso et al. 2021; Chuey et al., 2022; Dandurand, 2008; Pallen et al., 2022; Peyton et al., 2022). In this case, participants provided information about their screen size (no correlation between screen size and susceptibility for either of the two VIs or methods was observed: $p > .334$), and they were given control over the researcher's laptop to perform the task themselves. Before the experiment started participants were sent an online consent form. They were then given control over the researcher's computer to conduct the experiment, which allowed the participant to perform the experiment in a similar fashion as an in-person participant. During in-person testing, participants sat in front of the laptop displaying the experiment. They were instructed to use the left or right arrows to adjust the sizes of the stimuli and press "enter" when they believed the manipulated object matched the target size. The size was adjusted in steps of 5 pixels. Participants were encouraged not to overthink what they saw and to rely on their first impression. After completing the task, participants filled out a brief demographic questionnaire, and debriefing was provided. The task took approximately 10 minutes to complete

Analytic Plan

Similarly to the above experiment, the data underwent screening to detect outliers, and 'winsorising' was employed as a method to handle all outliers. To confirm normal distribution, visual inspections of the histograms and normal Q-Q plots were conducted. Subsequently, two two-way mixed-design ANOVAs were performed on both RT and susceptibility data (dependent variables), which were averaged within participants and sex (independent variable). The susceptibility score was calculated as the difference between the size of the comparison stimuli and the manipulated stimuli (in other words their PSEs). Any potential differences were followed up with planned comparisons using independent samples t-tests and paired samples t-tests to determine group variances. Additionally, correlations were carried out to investigate the relationships between different illusions among females and males, along with their respective RTs. Effect sizes were measured using Cohen's *d*. Corresponding Bayes Factors were calculated separately for each analysis, with no specific prior specified. A Bayes Factor of three and above, which will be considered as evidence for the alternative hypothesis, while a Bayes Factor of less than 1/3, will be considered as evidence pointing toward for the null hypothesis (Jarosz & Wiley, 2014).

Results

Outliers

For females' RTs, two outliers in the Ebbinghaus illusion were 'winsorised' down from 38 and 32 seconds to 27 seconds. In the case of males, a total of 10 values were 'winsorised' down. Specifically, four values were decreased in the Ebbinghaus illusion; from 49, 35, 32, and 29 to 27 seconds, and another four in the Muller-Lyer illusion; from 41, 39, 32, and 30 to 27 seconds. Similarly, among females, two values in the Ebbinghaus illusion were 'winsorised' up from -0.29 and -0.27 to -0.25, and one was reduced from 0.1 to -0.01. Additionally, for the Muller-Lyer one value was 'winsorised' down from -0.25 to -0.36. In the male sample, three values were 'winsorised'. One value was adjusted up for the Ebbinghaus illusion from -0.27 to -0.25. Two values were 'winsorised' down for the Muller-Lyer illusion from -0.17 to -0.25.

Normality of the Data Set

Akin to the above experiment, the experimental variables have mostly violated the assumptions of normality, as indicated by the Shapiro-Wilk test. However, as we have previously argued, the F-Tests intended to be used in this study are known to be robust to deviations from normal distribution (Blanca et al., 2017; Khan & Rayner, 2003). Therefore, to confirm normal distribution, we conducted visual inspections of Q-Q plots and histograms. The data exhibited characteristics of a normal distribution, which aligns with the principle of the central limit theorem, suggesting that large datasets (with a sample size greater than 30) tend to follow a normal distribution (Kwak & Kim, 2017).

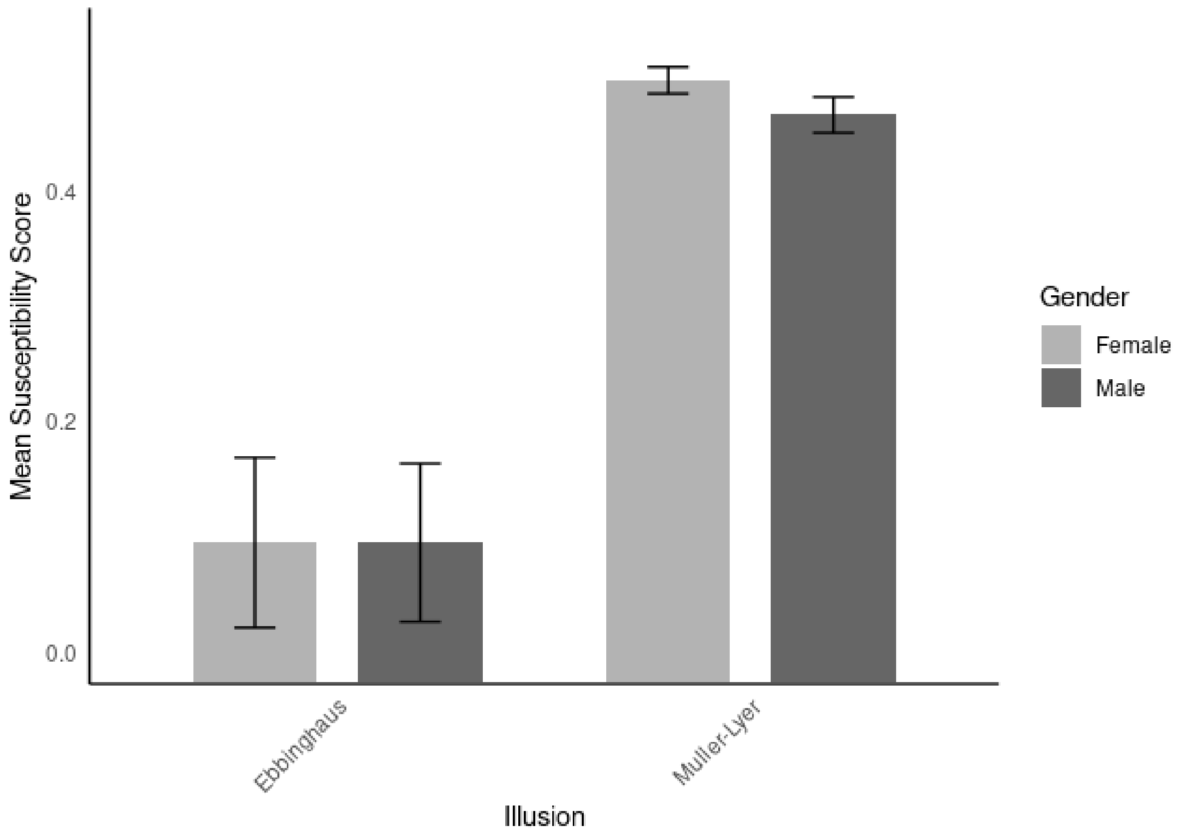
Two-Way Mixed-Design ANOVAs

Susceptibility Scores Analysis.

The assumptions of equality of variances as measured by Levene's test have been met for the Muller-Lyer illusion (p = .018). Participants' susceptibility scores were entered into a two-way (sex: male, female) x (VIs: Ebbinghaus, Muller-Lyer) mixed ANOVA. There was a main effect of illusion; $F(1, 118) = 1736.06$, $p < .001$, $\eta p^2 < 0.94$, $BF_{10} = 2.502\text{x}10^{+14}$ with participants being more susceptible to the Muller-Lyer (M = -0.51, SD = 0.11) illusion than the Ebbinghaus illusion (M = -0.12; SD = 0.06), paired samples t-test; $t(119) = 41.32$, $p < .001$, $d = 3.77$, $BF_{10} = 5.060\text{x}10^{+68}$. There was no main between-subject effect of sex; $F(1, 118) = 2.38$, $p = .126$, $\eta p^2 < 0.01$, $BF_{10} = 0.60$; and no sex x illusion susceptibility interaction; $F(1, 118) = 3.03$, $p = .085$, $\eta p^2 < 0.01$, $BF_{10} = 0.97$. See Figure 3 for the visualisation of the data.

Figure 3

Mean Susceptibility Scores Between Females and Males on the Ebbinghaus and Muller-Lyer illusions



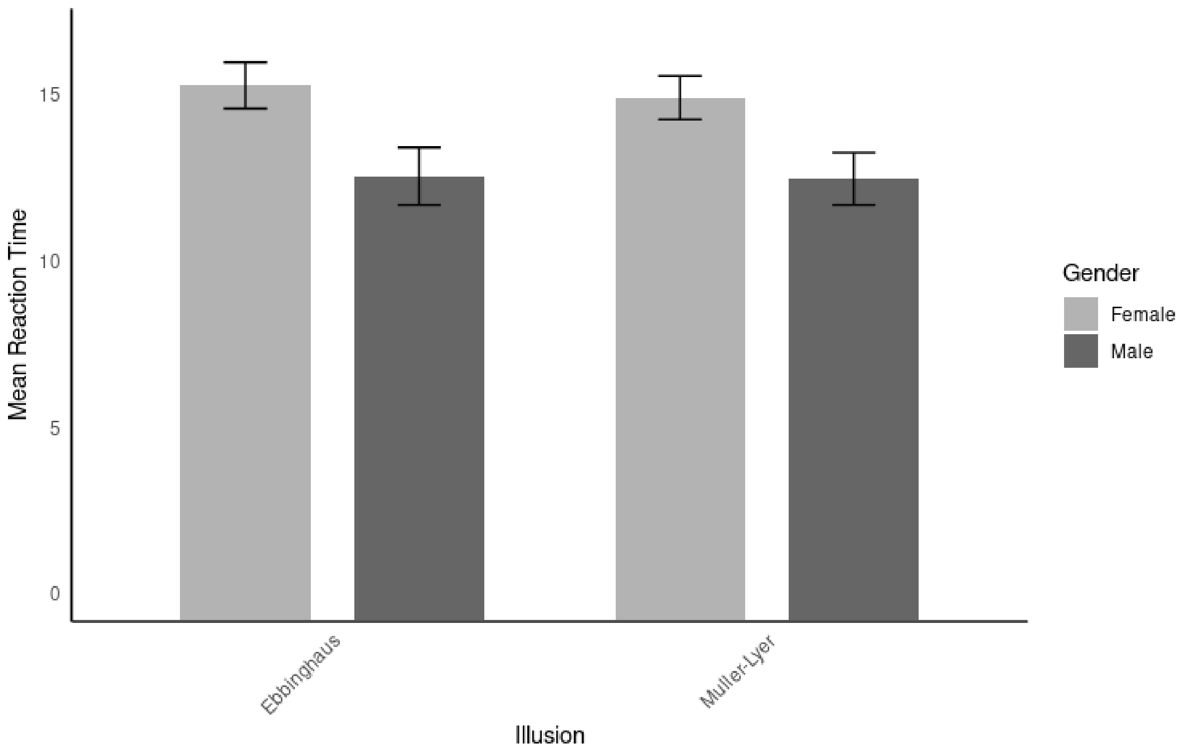
Note. The error bars represent the standard error. For the graph, the values have been transformed from negative to positive values for an easier interpretation.

Reaction Times Analysis.

The assumptions of equality of variances as measured by Levene's test have been met for both VIs ($p > .088$). Participants' susceptibility scores were entered into a two-way (sex: male, female) x (RTs to VIs: Ebbinghaus, Muller-Lyer) mixed ANOVA. We observed no main effect of RTs to VIs; $F(1, 118) = 0.28$, $p = .597$, $\eta p^2 < 0.01$, $BF_{10} = 0.12$, and a main between-subjects effect; $F(1, 118) = 6.13$, $p = .015$, $\eta p^2 = 0.05$, $BF_{10} = 2.41$. Across both VIs, females were significantly slower ($M = 31.71$, $SD = 9.67$) than males ($M = 25.65$, $SD = 12.56$) independent samples t-test; $t(118) = -2.48$, $p = .015$, $d = -0.45$, $BF_{10} = 2.98$. Furthermore, females *(M* = 16.05, *SD* = 5.39) having significantly longer RTs to the Ebbinghaus illusion compared to males (*M* = 13.32, *SD* = 6.7), independent samples t-test; $t(118) = -2.46$, $p = .015$, $d = -0.50$, $BF_{10} = 2.87$. Also, for the Muller-Lyer illusion, females' RTs (*M* = 15.68, *SD* = 5.04) were significantly longer than males' [(*M* = 13.24, *SD* = 6.08, independent samples t-test; $t(118) = -2.26$, $p = .026$, $d = -0.41$, $BF_{10} = 1.89$)]. Finally, there was no significant RTs to VIs x sex interaction; $F(1, 118) = 0.34$, $p = .560$, $\eta p^2 < 0.01$. $BF_{10} = 0.10$. See Figure 4 for the visualisation of the data.

Figure 4

Mean Reaction Times for Females and Males for both the Ebbinghaus and Ponzo Illusions



Note. The error bars represent the standard error. For the graph, the values have been transformed from negative to positive values for an easier interpretation.

In-Person Versus Online.

Participants' susceptibility scores were entered into a 2-way (mode of testing: online, in-person) x 2 (illusion: Ebbinghaus, Muller-Lyer) mixed ANOVA. We observed a main effect of VIs: $F(1, 118) = 1717.51$, $p < .001$, $\eta p^2 = 0.94$, $BF_{10} = 5.177x10^{+13}$. There was no main between-subject effect (online versus in-person) = $F(1, 118) = 2.27$, $p = .134$, $\eta p^2 = 0.02$, $BF_{10} = 0.66$, and there was no interaction $F(1, 118) = 3.48$, $p = .065$, $\eta p^2 = 0.03$, $BF_{10} = 128$, suggesting that online testing via Microsoft Teams does not affect the data quality.

Correlations

We assessed the correlations between VIs for separate sexes, as well as the whole cohort, as well as between RTs and VIs susceptibility scores. Pearson's correlations showed that the two VIs are significantly correlated with each other [$r(1, 118)= .311$, $p < .001$, $BF_{10} = 41.08$). However, correlations between VIs susceptibility and RTs failed to reach significance (ps > .165; all $BF_{10} < 0.30$).

Discussion

Despite females exhibiting longer RTs across both VIs, no significant sex differences in VI susceptibility were detected. This contradicts the notion that prolonged exposure reduces magnitude of VIs. Furthermore, it suggests that sex differences in VI susceptibility are contingent upon the methods used. Contrary to Experiment 1, we observed that the Muller-Lyer illusion produces a stronger illusory effect compared to the Ebbinghaus illusion, which suggests that methodological differences can affect the magnitudes of illusory effects. These findings provide further insight into how methodological differences can explain disparities in previous research on VIs, as illusion magnitudes are not identical across methods. The testing using MOA has also been shown to be reliable when conducted online via Microsoft Teams. Finally, to study the illusions' magnitudes within a single sample, a different version of the 2AFC method (without randomisation) was conducted. This allowed for comparing the illusion's magnitudes across methods as well as potential sex differences in methods that have differing task demands.

Experiment 3 – 2AFC without Randomisation

Introduction

As Experiment 1 and 2 provided differing sex trends in susceptibility to the Ebbinghaus illusion, another method was included. This time, the physical differences were changing gradually, rather than randomly as in Experiment 1, which should remove any bias, such as focusing on one set of circles most of the time. By utilising three different methods, we aim to provide the most compelling, up-to-date, comparison of different method across sexes.

Method

Participants

The participants were the same as in Experiment 2.

Apparatus and Materials

Akin to Experiment 2, this experiment was designed using Unity3D® Gaming Engine, and the VIs were modelled based on the works of Doherty et al. (2010) and Sperandio et al. (2016). Participants completed the task on the same battery of VIs. Each trial was followed by a short mask to prevent an animation effect (i.e. lines or circles expanding). There were 80 trials for both the Ebbinghaus and Muller-Lyer illusions. The steps for the Ebbinghaus illusion varied in 10 pixels steps, starting from the manipulated circle being half as big or half as small as the other circle which was held constant. There were four conditions where the target circle was manipulated (big surroundings starting big, big surroundings starting small, small surroundings starting big, and small surroundings starting small), which were counterbalanced. The same procedure was done for the Muller-Lyer illusion, with the exception that the manipulated line varied in steps of 20 pixels.

Procedure

The procedure was identical to Experiment 2, except that participants were asked not to overthink what they saw, to answer as quickly and accurately as possible, and to make their best guess if unsure. Participants responded by pressing a relevant key on the keyboard to decide which target was longer or bigger, depending on the VI.

Analytic Plan

Experiment 3 used the same statistical analyses as Experiment 2. Using SPSS, PSEs were calculated for each participant. The PSE was estimated by fitting a psychometric function to the proportion of trials in which the comparison stimulus was judged as larger than the reference stimulus. The size difference between the two stimuli was systematically manipulated across trials. The PSE corresponds to the point on the psychometric curve where participants were equally likely to choose either stimulus (i.e., at 50% of "comparison larger" responses). This represents the size difference at which the two stimuli appeared subjectively equal in size. In other words, the point at which participant switched between the two targets, represents their PSE. This was then averaged across the experiment.

Results

Outliers

Outliers were handled using the method of ‘winsorising’ as in Experiment 2. For the RT analysis, all outliers were ‘winsorised’ down. We detected two outliers in the male sample: one for the Ebbinghaus illusion (5.73 to 3.5 seconds) and one for the Muller-Lyer illusion (7.28 to 4 seconds). In the female sample, a total of eight outliers were observed. Three for the Ebbinghaus illusion, which were reduced to 3.5 seconds from 4.6, 4.49, and 4.29 seconds. For the Muller-Lyer illusion, five values were reduced from 3.85, 4.2, 4.51, 4.62, and 5.02 to 3.3 seconds. A total of four outliers in susceptibility scores were observed among females (none for males). For the Ebbinghaus illusion, two scores were ‘winsorised’ down from 0.08 and 0.07 to 0.02, while for the Muller-Lyer illusion, one score was decreased down from 0.16 to -0.07, and one was increased from -1.2 to -0.55.

Normality of the Data Set

Shapiro and Wilk's tests showed that susceptibility scores are normally distributed for both illusions and both groups ($p < .155$), except for the Muller-Lyer illusion scores in females ($p = .033$). None of the RTs for either group and illusion were normally distributed (all $p > .001$), however, in line with the arguments raised in Experiment 2, normal distribution was assumed (visual inspection of histograms and Q-Q plots indicated normal distribution).

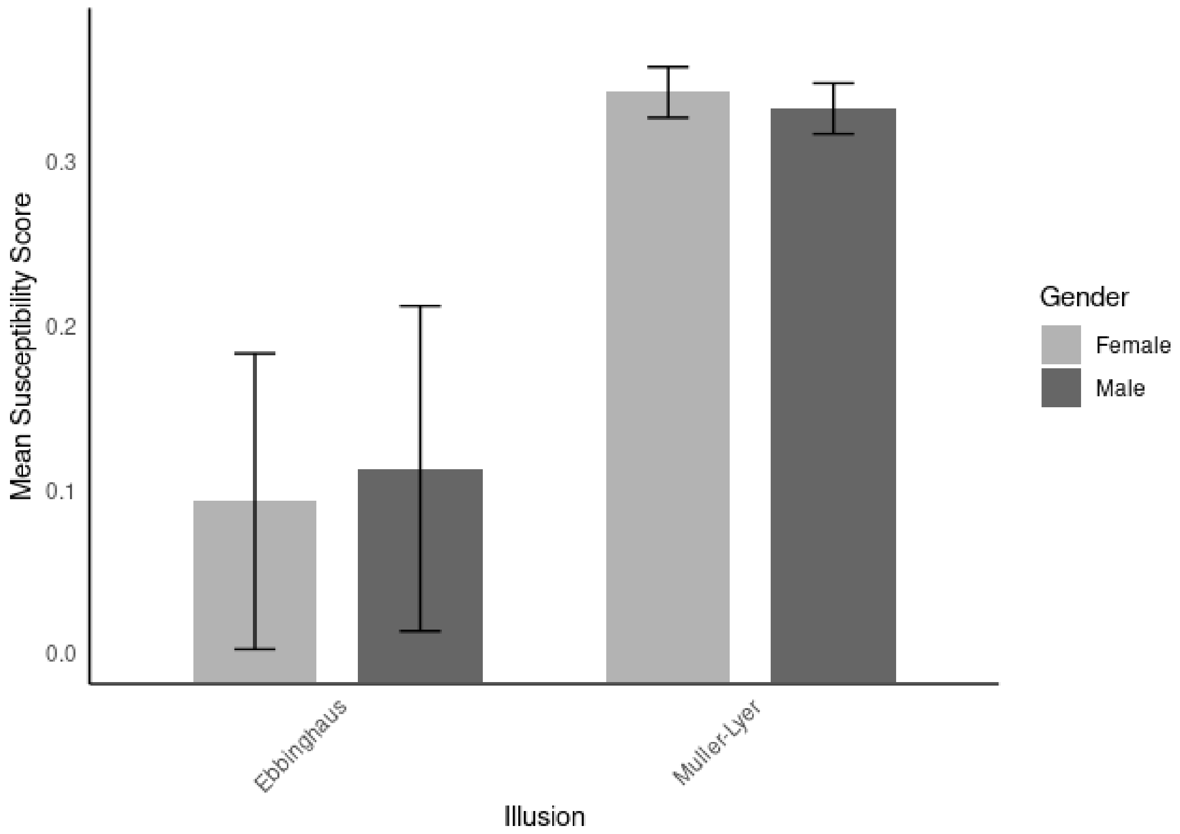
Two-Way Mixed-Design ANOVAs

Susceptibility Scores Analysis.

The assumptions of equality of variances as measured by Levene's test have been met for both illusions ($p > .397$). Participants' susceptibility scores were entered into a two-way (sex: male, female) x (illusion: Ebbinghaus, Muller-Lyer) mixed ANOVA. We observed a main effect of VIs; $F(1, 118) = 334.68$, $p < .001$, $\eta p^2 = 0.74$, $BF_{10} = \infty$. Again, participants responded less accurately to the Muller-Lyer ($M = -0.35$, $SD = 0.13$) rather than the Ebbinghaus illusion ($M = -0.12$, $SD = 0.08$), indicating greater susceptibility, paired samples t-test: $t(118) = 18.22$, $p < .001$, $d = 1.67$, $BF_{10} = 1.416 \times 10^{+33}$. There was no main between-subject effect; $F(1, 118) = 0.21$, $p = .802$, $\eta p^2 < 0.01$, $BF_{10} = 0.15$; as well as there was no significant VIs x sex interaction; $F(1, 118) = 0.5$, $p = .481$, $\eta p^2 < 0.01$, $BF_{10} = .14$. Collectively, these results indicate a lack of sex differences in susceptibility to these two VIs using a 2AFC design without randomisation. See Figure 5 for the visualisation of the data.

Figure 5

Mean Susceptibility Scores for Females and Males for both the Ebbinghaus and Ponzo Illusions



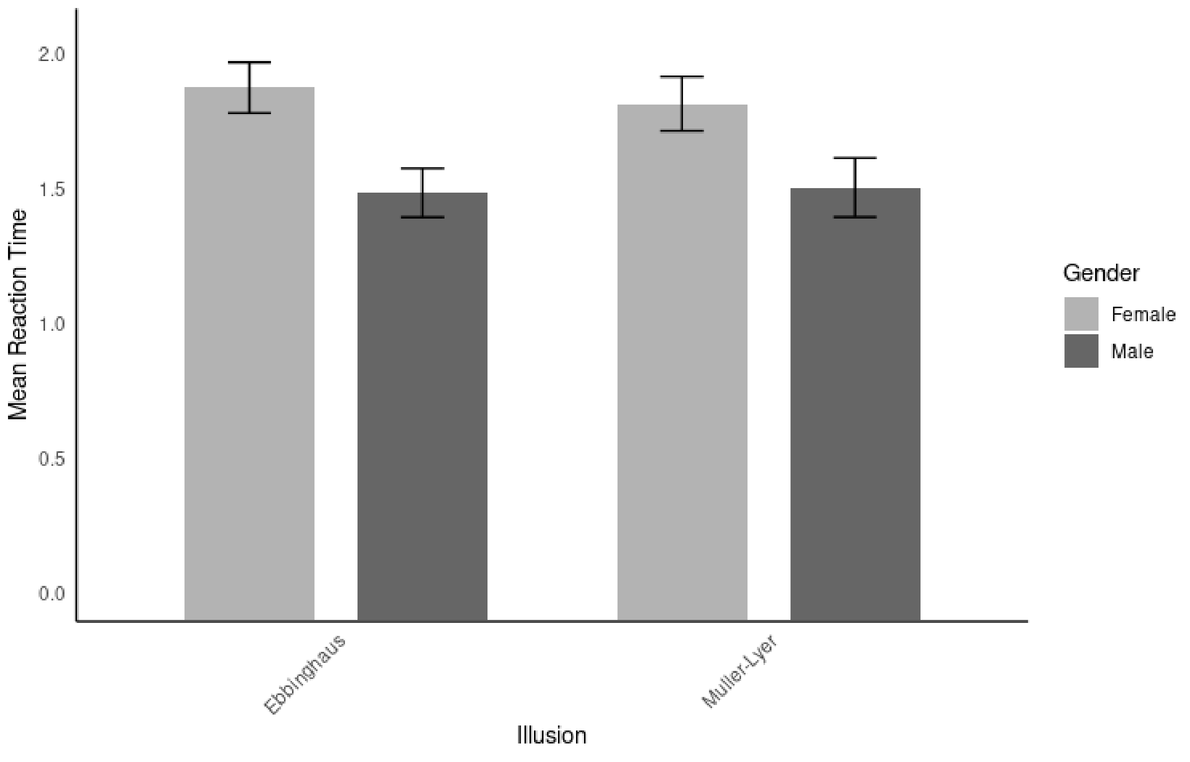
Note. The error bars represent the standard error. For the graph, the values have been transformed from negative to positive values for an easier interpretation.

Reaction Times Analysis.

The assumptions of equality of variances as measured by Levene's test have been met for both illusions (*p*s >.211). Participants' susceptibility scores were entered into a 2-way (sex: male, female) x (RTs to VIs: Ebbinghaus, Muller-Lyer) mixed ANOVA; $F(1, 118) = 0.43$, $p = .515$, $\eta p^2 < 0.01$, $BF_{10} = 0.14$. We observed a significant between-subject effect; $F(1, 118) = 6.83$, $p = .010$, $\eta p^2 < 0.06$, $BF_{10} = 2.65$, again showing that females viewed both VIs for a longer period of time than males. Averaged across both VIs, the RTs were significantly longer for females ($M = 3.87$, $SD = 1.47$) than males ($M = 3.18$, $SD = 1.51$), independent samples t-test; $t(118) = -2.58$, $p = .011$, $d = -0.47$, $BF_{10} = 3.76$. Females' RTs (in seconds) for the Ebbinghaus illusion ($M = 1.97$, $SD = 0.73$) were significantly longer than those of males ($M = 1.58$, $SD = 0.7$), independent samples t-test; $t(118) = 2.99$, $p = .003$, $d = 0.55$, $BF_{10} = 10.29$. Also, for the Muller-Lyer illusion, females' RTs ($M = 1.91$, $SD = 0.78$) were significantly longer than males' ($M = 1.6$, $SD = 0.85$), independent samples t-test; $t(118) = 2.08$, $p = .039$, $d = 0.38$, $BF_{10} = 1.35$. Finally, there was no significant interaction between sex and RTs; $F(1, 118) = 1.37$, $p = .244$, $\eta p^2 = 0.01$, $BF_{10} = 0.15$. See Figure 6 for the visualisation of the data.

Figure 6

Mean Reaction Times for Females and Males for both the Ebbinghaus and Ponzo Illusions



Note. The error bars represent the standard error. For the graph, the values have been transformed from negative to positive values for an easier interpretation.

In-Person Versus Online.

Again, participants' susceptibility scores were entered into a 2-way (mode of testing: online, in-person) x 2 (illusion: Ebbinghaus, Muller-Lyer) mixed ANOVA. Similarly, these participants did not differ in their susceptibility when tested online versus in-person, as we showed a main effect of VIs: $F(1, 118) = 331.30$, $p < .001$, $\eta p^2 = 0.74$, $BF_{10} = 8.578x10^{+14}$ and no main between-subjects effect: $F(1, 118) = 0.89$, $p = .348$, $\eta p^2 < 0.01$, $BF_{10} = 0.23$. Finally, there was no interaction: $F(1, 118) = 1.41$, $p = .237$, $\eta p^2 = 0.01$, $BF_{10} = 0.32$.

Correlations.

As in the previous experiments, we conducted Pearson's correlations between RTs and susceptibility scores. All correlations failed to reach significance (*p*s > .074, all Bayes Factors < 0.12), except for the correlation between the RTs between both the Ebbinghaus and Muller-Lyer illusions; $r(118) = .892$, $p < .001$, $BF_{10} = 1.031x10^{+39}$, indicating that prolonged time to respond to the Ebbinghaus illusion is associated with longer time to respond to the Muller-Lyer illusion, and vice versa.

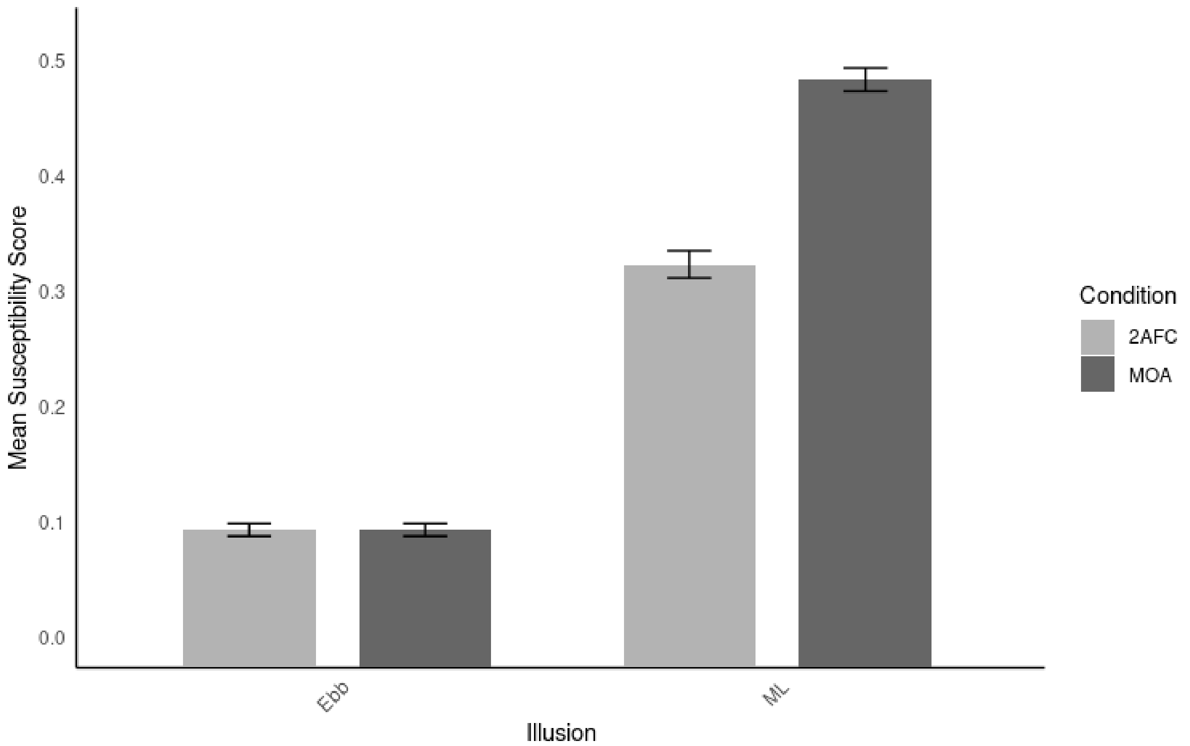
Comparison of PSEs Across Methods.

Finally, we conducted a comparison between the PSEs from Experiments 2 and 3. To do so, we conducted two separate paired samples t-tests. Sex was omitted as a factor, as the vast majority of the previous studies do not consider sex differences in their analyses, hence here we were only interested in comparing the overall PSEs between the two methods. In the first, we showed no difference in PSEs for the Ebbinghaus illusion between the MOA (M = - 0.12, SD = 0.06) and the 2AFC without randomisation (M = - 0.12, SD = 0.07); $t(118) = 0.50$, $p = .619$, $d = 0.05$, $BF_{10} = 0.11$. In the latter for the Muller-Lyer illusion, we observed a significant difference indicating greater susceptibility using the method of adjustment (M = - 0.51, SD = 0.11) compared to the 2AFC without randomisation (M = - 0.35, SD = 0.13); $t(118) = 13.50$, $p < .001$, $d = 1.23$, $BF_{10} = 4.043x10^{+22}$. For completeness, we also tested the difference across sexes. This difference remained after analysing both sexes separately (*p*s < .001, with all Bayes Factors providing extremely strong support for the alternative hypothesis). Susceptibility to the Ebbinghaus illusion across both methods correlated moderately [$r(118)$ =

.603, $p < .001$, $BF_{10} = 2.746x10^{+10}$], while susceptibility to the Muller-Lyer illusion across both methods correlated less strongly [$r(118) = .393$, $p < .001$, $BF_{10} = 1964.24$]. Also, RTs across two methods for the Ebbinghaus and Muller-Lyer illusions correlated positively: $r(118) = .587$, $p < .001$, $BF_{10} = 4.889x10^{+9}$ and $r(118) = .526$, $p < .001$, $BF_{10} = 1.672x10^{+7}$, respectively. See Figure 7 for the visualisation of the data.

Figure 7

Mean Susceptibility for Females and Males Across Different Methods



Note. The error bars represent the standard error. For the graph, the values have been transformed from negative to positive values for an easier interpretation.

Discussion

Despite females exhibiting longer RTs, their VI susceptibility does not differ from their male counterparts. Interestingly, here we observed that for the Muller-Lyer illusion the PSE was a third larger when using MOA compared to 2AFC. These findings underscore the role of methodology and its effect on obtained data, suggesting that some VI are more sensitive to changes in methodology than others. Importantly, these findings suggests that the cut-off for perceived equality differs when participants are forced to make a choice between two stimuli and what they perceive to be the true match.

General Discussion

Across three experiments, using three distinct methods, we investigated sex differences in susceptibility to the Ebbinghaus and Muller-Lyer illusions across males and females. Our first hypothesis that sex differences, if any, would be constant across VI response methods was not supported. Males exhibited reduced susceptibility to the Ebbinghaus illusion, but only in Experiment 1 when the 2AFC after Phillips et al. (2004) was used. MOA and 2AFC without randomisation produced differing magnitudes for the Muller-Lyer illusion, again contradicting our hypothesis that PSEs for both VIs would be comparable across methods. Next, RTs and VIs susceptibility only correlated for the Ebbinghaus illusion when the Phillips et al. (2004) method was used, contradicting our hypothesis that such correlations will be consistent across VIs and methods.

This study represents one of the first investigations to highlight methodological disparities in research on VIs. It becomes apparent from our findings that selecting appropriate methods for studying VIs is far from straightforward. Prior investigations have often overlooked this aspect of study design, seemingly opting for convenience (which may stem from greater ease of coding a particular method or inheriting a particular method from other studies) over empirical grounding, as most studies do not provide justifications for their selection of methodology. Our research underscores that diverse methods may yield different outcomes due to reasons, which currently require further research. For instance, our study revealed that males exhibited diminished susceptibility to the Ebbinghaus illusion, correlating with prolonged reaction times, indicating a speed-accuracy trade-off. Conversely, this pattern did not hold for alternative methods, raising concerns regarding the reliability of specific methodologies. Considering the current findings, a conclusion based on previous findings might be biased by the methodology used, rather than genuine differences in visual perception. In other words, have we tested the sex differences using only the Ebbinghaus illusion and 2AFC after Philips et al. (2004), we could safely conclude that there is a genuine sex difference. However, selecting a different method, would show no sex effect. It is therefore likely, that different methods in different populations (e.g., autism or schizophrenia) might show differing outcomes. Manning et al. (2017) have shown in their research on autistic children, that the Muller-Lyer illusion is susceptible to atypical response strategies, as children with autism were more susceptible to the illusion but only when MOA was used. Consequently, it becomes evident that for the field to progress and engender confidence in its conclusions, greater emphasis must be placed on recognising and addressing methodological distinctions. Given the larger magnitude observed for the Muller-Lyer illusion, using MOA, it appears that this method might be more suitable to detect differences in VIs susceptibility, although further research is required. This sentiment aligns with the assertions made by Wincza and colleagues (2024), who argue that many findings within the field may be contingent upon the particular type of VI under examination, as well as the methodology employed, rather than representing a generalised attribute to this particular VI as a whole. Therefore, future studies should employ more than one method to study the intended phenomenon, like VI susceptibility, using a range of stimuli variations that differ in their layout and magnitude, to establish whether previously observed trends are contingent upon the specific method or stimuli type used.

Another noteworthy aspect for future investigations pertains to the disparity in illusion magnitudes observed between the MOA and the 2AFC without randomisation. While participants exhibited identical performance on the Ebbinghaus illusion using both methods (M = -0.12), thereby validating results established by Cretenoud and colleagues (2021), a discrepancy emerged in the magnitudes of the Muller-Lyer illusion. In the case of the MOA, participants displayed a larger susceptibility compared to the 2AFC without randomisation. This finding contradicts the results reported by Cretenoud and colleagues (2021), who found no variance in susceptibility across these methods. A plausible explanation could be attributed to the sample size; their study, comprising 20 participants, might have been insufficient to detect such a difference, unlike the larger sample utilized in this study (*n* = 120). Nevertheless, this finding implies that the threshold for perceived equality varies when participants are required to choose between two stimuli compared to when they identify what they believe to be the true match. In situations of uncertainty, participants' reasoning (about how the illusion works) is likely to interfere with their perception, therefore when they are unsure of their choice, they select the non-illusory (thus correct) line. On the contrary, using the MOA task, they can provide the experimenter with what they believe to be the correct response, which increases their susceptibility. This suggests that different decision-making criteria or certain strategies are employed when responding to a Muller-Lyer illusion task, depending on the method used. This might exaggerate (or reduce) the perceptual differences in other domains such as clinical research, where apparent differences in susceptibility between clinical and non-clinical groups are observed (e.g., schizophrenia – see Costa et al., 2023 or autism; see Manning et al., 2017).

It is crucial to note that adjustment methods like MOA typically measure the magnitude of the illusion (i.e., the extent of deviation in size between the target and reference), while forced-choice paradigms (like the 2AFC) measure accuracy and discrimination ability in detecting physical differences between targets (Kingdom & Prins, 2016). This suggests that the ability to discern a size difference in the Muller-Lyer illusion may have a lower threshold (PSE) than the perceptual threshold for perceived length equality. Further research is imperative to delve into methodological differences across various VIs, including those not studied here, like the Ponzo illusion.

Regarding the hypothesis on RTs, our results offer additional support for the assertions made by Bressan and Kramer (2021) that unrestricted presentation times weaken the Ebbinghaus illusion. Our analysis revealed a positive correlation between RTs and Ebbinghaus susceptibility, but this correlation was evident only for the Phillips et al. (2004) method, similar to the approach employed by Bressan and Kramer. Based on our observed correlation, we can suspect that males spent more time examining the illusion, leading to more accurate responses. Interestingly, this pattern was not observed for females nor the Muller-Lyer illusion. Notably, this trend was also absent in other methods, where females, although not significantly, took longer to inspect the illusions. The time-accuracy trade-off may only apply to some VI, and to methods where the trial order is fully randomised – the trials do not increase or decrease systematically as in Experiment 3 but appear more randomly, perhaps requiring more inspection time. Future studies should investigate the interplay between inspection time and methodology further.

When it comes to sex differences in VIs susceptibility, our findings replicated those of Phillips et al. (2004), who, using the same method, demonstrated that males exhibit lower susceptibility to the Ebbinghaus illusion. They proposed that males are less context-sensitive than females, thereby considering fewer contextual cues and thus reducing inference from the surrounding circles. However, these assertions warrant reconsideration. Our extensive analysis, employing three different methods, revealed that females do not exhibit differential susceptibility to the Ebbinghaus illusion in two out of three methods. Consequently, these results imply that susceptibility to the Ebbinghaus illusion is influenced by the method used, rather than a general ability to integrate contextual cues (alternatively, one could assume that if females took a longer time to respond, this effect would diseappear). Phillips and colleagues' (2004) method presents the illusion in a randomized order, in contrast to the 2AFC without randomisation, where the illusion's target is gradually manipulated. When the illusion is manipulated gradually, interference from previous trials may impact subsequent responses (carry-over effects), leading to the emergence of response biases that could be equally manifested by both sexes. However, these conjectures necessitate further empirical testing.

The absence of significant sex differences overall aligns with findings from other studies investigating the Ebbinghaus and Muller-Lyer illusions. Dewar (1967), McGraw (n.d.), Porac and colleagues (1979), and Shaqiri et al. (2018) all reported no significant differences. In light of these results, we conclude that despite variations in top-down and bottom-up processing between females and males (e.g., Baron-Cohen, 2002; Sargezeh et al., 2019; Voyer et al., 1995), these processes appear not to be linked with neurotypical adults' susceptibility to VIs. Furthermore, our study demonstrates that susceptibility to VIs is a heterogeneous phenomenon.

One potential concern with the current study is the absence of a strict between- or within-participant design. It is conceivable that facing two similar tasks may introduce carry-over effects, wherein experiencing one condition could impart certain expectations or beliefs while conducting the second task (Brooks, 2012), especially when confronted with an identical illusion. It is plausible that participants, upon encountering the illusion for the second time, developed specific ideas about the workings of any given illusion, potentially influencing their subsequent responses – although counterbalancing was employed in this study, it remains a plausible concern for this study. Also, despite no statistically significant differences observed between participants tested online and in-person (and a body of evidence suggesting that online research tends to replicate lab-based studies, e.g., Chuey et al., 2022), no studies have directly investigated this across a wider batter of VIs – with this study being the first of its kind to investigate this.

Future research should delve into the reasons underlying males' increased response accuracy in the Ebbinghaus illusion task, specifically when employing the Phillips et al. (2004)

method. Two potential avenues for investigation are proposed. Firstly, a systematic increase in the number of trials (Phillips' method involves 24 trials, whereas the 2AFC without randomisation includes 80 trials) could unveil whether participants' responses become more bias-driven in the later stages of the experiment. Wincza and colleagues (2024) suggest that as the duration of the experiment lengthens, participants are more likely to rely on response bias (systematically preferring one type of answer over another, Morgan et al., 2013) rather than genuine visual discrimination. In alignment with the findings of Papageorgiu and colleagues (2020) indicating that females and males adopt distinct semantic strategies (males exhibit faster and more automatic responses, while females approach the task more slowly and deliberately), the emergence of such strategies is plausible. As discussed above, with prolonged exposure to the task, females might get quicker, which in turn might diminish any differences in susceptibility. Hence, when visual discrimination is replaced by a strategic approach or a change in providing responses, any differences in susceptibility might be compensated by the response bias.

The significance of this research extends beyond investigating sex differences in susceptibility to VIs. It holds relevance for drawing conclusions in clinical research contexts as well. For instance, Barch et al. (2012) noted that attention lapses could contribute to susceptibility in schizophrenia. Similarly, Zouraraki and colleagues (2023) found that heightened suspiciousness correlated with increased susceptibility to the Muller-Lyer illusion when evaluating schizotypal traits. What was previously attributed to genuine perceptual and organisational distinctions may, in fact, stem from the utilisation of differing exposure times, strategies and cognitive interference during tasks. Future research should investigate this closely. Secondly, future research should also focus on how participants experience the task, and whether they develop any strategies to deal with the task. Therefore, we suggest that future research should also investigate VIs susceptibility from a qualitative point of view.

Conclusion

Through three experiments, we presented compelling evidence that different methodologies to study VIs susceptibility differ in their magnitudes and outcomes. We observed a general absence of sex differences in susceptibility to the Ebbinghaus and Muller-Lyer illusions, as well as different methods differed in the magnitude of the illusion observed – the magnitude of the Muller-Lyer illusion was larger by a third when MOA was used compared to the 2AFC without randomisation. Our results offer insights for future research regarding methodological choices. We illustrated that, despite certain overlaps, different methods yield varying results, differing not only in outcome but also in magnitude, suggesting that the method of adjustment is a more sensitive method, at least for some VIs. Finally, RTs largely do not seem to relate to VIs susceptibility.

Chapter V

Thesis Continuity Statement

Both Chapter III and IV found that in childhood and early adulthood, VI susceptibility is relatively stable across response methods. Chapter V takes a different approach and aims to investigate a factor that has not been previously studied in relation to VIs - visual expertise. In Chapter II, the influence of visual experience on susceptibility to VIs was discussed and highlighted as a potential reason why children's susceptibility to VIs differs from adults'. Taking this novel approach, we investigated whether individuals accustomed to working with pictorial depth, such as radiologists and radiographers, exhibit different levels of susceptibility to VIs. This approach promises insights into whether professional training influences susceptibility to VIs, potentially shedding light on developmental changes in susceptibility observed in children. This approach will also help to understand the role of expertise in pictorial depth perception and context integration. To investigate this, trainee radiologists, certified radiologists, reporting radiographers, radiography, medical, and psychology students were tested using fours VIs; the Ebbinghaus, Ponzo, Muller-Lyer, and Shepard Table Tops illusions. This research will provide insight into how extensive expertise in perceiving pictorial depth affects susceptibility to VIs, where apparent depth cues are thought to contribute to the illusory effect. This Chapter has been published in *Scientific Reports*.

Wincza, R., Hartley, C., Donovan. T., Linkenauger, S., Crawford, T., Griffiths, D., & Doherty, M. (2025). Specific visual expertise reduces susceptibility to visual illusions. *Scientific Reports*, *15*, 5948. https://doi.org/10.1038/s41598-025-88178-y

Abstract

Extensive exposure to specific kinds of imagery tunes visual perception, enhancing recognition and interpretation abilities relevant to those stimuli (e.g. radiologists can rapidly extract important information from medical scans). For the first time, we tested whether specific visual expertise induced by professional training also affords domain-general perceptual advantages. Experts in medical image interpretation (n = 44; reporting radiographers, trainee radiologists, and certified radiologists) and a control group consisting of psychology and medical students (n = 107) responded to the Ebbinghaus, Ponzo, Müller-Lyer, and Shepard Tabletops visual illusions in forced-choice tasks. Our results show that medical image experts were significantly less susceptible to all illusions except for the Shepard Tabletops, demonstrating superior perceptual accuracy. These findings could possibly be attributed to a stronger local processing bias, a by-product of learning to focus on specific areas of interest by disregarding irrelevant context in their domain of expertise.

Keywords: medical image perception, context integration, neuroplasticity, size constancy mechanisms, visual illusions

Specific Visual Expertise Reduces Visual Illusions Susceptibility

Expertise is the culmination of a lengthy and deliberate process of acquiring and mastering a specific skill (Ericsson et al., 1993). Domains necessitating extensive visual expertise include face processing (Piepers & Robbins, 2012), chess (Reingold & Sheridan, 2011), and radiology (Sheridan & Reingold, 2017; Waite et al., 2019). This study focuses on expertise in medical image interpretation, specifically radiology and radiography. Much attention has been allocated to the study of global perception in visual expertise. However, it remains unknown whether specific visual expertise confers general changes in perception. Given that 60 to 80% of diagnostic errors are perceptual in nature (Bruno et al., 2015), the visual perceptual abilities of radiologists and radiographers should be examined. This study uses a visual illusion (VI) task to demonstrate that medical image interpretation abilities may extend beyond that domain of expertise.

Expertise in radiology encompasses deep knowledge of medical imaging, anatomy, and pathology. It relies on radiologists' advanced visual search patterns and ability to discern critical details in medical images (Waite et al., 2019). Here, we refer to radiographers and radiologists as experts, compared to the general public who will be referred to as non-experts. Interpretation of medical images involves a combination of cognitive (analysis and interpretation) and perceptual (visual search, visuospatial abilities) skills (Bruno et al., 2015; Corry, 2011; Kundel, 2006). Experts outperform non-experts in detecting abnormalities (e.g., Bertram et al., 2013; Cooper et al., 2009; Krupinsky, 2012), particularly with brief exposure times, ranging from 250 to 2000 milliseconds (Evans et al., 2013). With increasing experience, experts in medical image interpretation learn to focus on target-relevant areas while ignoring irrelevant content (Wolfe et al., 2016), resulting in quicker fixations on task-relevant areas (van der Gijp et al., 2017). Experts also develop specific expectations about what to look for in an image, suggesting that input from memory enhances their ability to detect abnormalities more rapidly (Sheridan & Reingold, 2017). These findings suggest that, through extensive exposure to specific stimuli, experts in medical image interpretation develop finely tuned visual search skills in their domain of expertise.

Previous theoretical models have proposed that superior perception abilities do not generalise beyond a specific domain of visual expertise (e.g., Gegenfurtner et al., 2023; Sheridan & Reingold, 2017). This assertion is underpinned by the belief that experts' superior performance within their respective domains is afforded by top-down influences. Top-down perception involves perceiving the global picture (seeing the forest before the trees), shaped by prior knowledge and expectations (Eldar et al., 2016). Experts utilise peripheral and parafoveal vision to analyse extensive portions of an image simultaneously (Nodine & Kundel, 1987; Nodine & Mello-Thoms, 2000; 2010; Swensson, 1980), implicating a top-down approach to visual processing. However, previous studies have reported that superior visual abilities conferred by expertise may not generalise beyond specific stimuli. For example, experts are no faster than non-experts at spotting the character Wally (Waldo in the U.S.) or the word NINA among distractors (Nodine & Krupinsky, 1998) and, even in tasks superficially resembling medical image searches, experts did not outperform non-experts (Moise et al., 2005). Similar findings have been documented in research concerning experts' visual search abilities (for overview, see Sheridan & Reingold, 2017) and memory tasks involving visual stimuli, such as objects or scenes (Evans et al., 2011).

Research has yet to investigate whether enhancements in experts' visual perception abilities are a product of specialist professional training (Birchall et al., 2015; Corry et al., 2011). Only two studies have addressed this issue. Bass and Chiles (1990) found a general absence of predictive relationships between experts' domain-general visual abilities (contrast sensitivity or visual acuity) and their ability to spot abnormalities in medical images. Sowden et al. (2000) found that, although experts exhibited improved contrast sensitivity, non-experts with no previous experience interpreting medical images also enhanced their ability to discern shade differences after practicing for 10 days. These findings provide mixed evidence about whether radiology training leads to lasting alterations in general visual perception.

In addition to visual search and memory abilities, at least two other skills are required for medical image interpretation: visual context integration and perceptual rescaling. Context integration refers to the ability to visually integrate different elements of a visual scene. With increasing experience, medical image interpretation experts may learn to focus on relevant areas and ignore irrelevant content (Wolfe et al., 2016). Furthermore, successful interpretation of medical images necessitates perceptually transforming a 2D image into a 3D scene, thereby achieving a more lifelike representation of the corresponding part of the human body (e.g., Smoker et al., 1984).

Both the ability to visually disregard illusion-inducing details and perceptual rescaling have been linked to VI susceptibility (Kaldy & Kovacs, 2003; Phillips et al., 2004; Yildiz et al., 2022). For example, when no surroundings are presented in the Ebbinghaus illusion, humans can correctly detect size differences of 2% between circles (Doherty et al. 2010). However, performance drops when a misleading context is applied, potentially due to illusory size differences. This makes VIs a valuable tool in the study of context integration ability. Relatedly, perceptual rescaling plays a pivotal role in accurately estimating the sizes of objects at varying distances in the 3D world (Gregory, 1963). The human visual system automatically rescales identically-sized objects placed at different distances, causing us to perceive them as equally sized, even though they project different visual angles onto the retina. However, these mechanisms can operate inappropriately in images. All the visual stimuli in a 2D image are roughly at the same real depth - the distance between the image and the eye - and perceptual rescaling mechanisms can result in illusory distortions in size perception. These effects are thought to operate in a number of visual illusions, such as the Ebbinghaus, Ponzo, Müller-Lyer, and Shepard's Tabletops illusions (Doherty et al., 2010; Yildiz et al., 2022; Gregory, 1963; Songhorabadi et al., 2022, respectively).

Context integration and perceptual rescaling mechanisms may result in illusory size differences, with both processes potentially interfering with judgements of objects in medical images. Acquired expertise through professional training may involve the ability to ignore irrelevant visual context when judging object size, a skill that might be absent amongst nonexperts. If this ability extends beyond the specific domain of medical imaging, we would predict experts in medical image interpretation to show superior size judgement in geometrical visual illusions that derive from inappropriate context integration and perceptual rescaling.

Thus mechanisms for context integration and perceptual rescaling can result in illusory size differences. Both potentially interfere with judgements of objects in medical images. Thus expertise plausibly involves the abilities to visually ignore irrelevant context when judging object size, including during perceptual rescaling. If these abilities extend beyond the specific domain of medical imaging we predict experts in medical image interpretation will show superior size judgement in a specific group of geometrical visual illusions, those in which illusory effects derive from inappropriate context integration and perceptual rescaling.

For the first time, we tested whether specific visual expertise induced by professional training affords domain-general perceptual advantages in terms of reduced susceptibility to visual illusions. Experts in medical image interpretation (reporting radiographers, trainee radiologists, and certified radiologists) and a control group consisting of psychology and medical students were presented with the Ebbinghaus, Ponzo, Müller-Lyer, and Shepard Tabletops visual illusions via forced-choice tasks. Participants were tested on their size discrimination, an ability that draws on both context integration and perceptual rescaling (see Wincza et al., 2024; Yildiz et al., 2022 for reviews). We hypothesised that experts in medical image interpretation would be less susceptible to VIs, responding more accurately as a result of increasingly localised and stimulus-driven perception conditioned through their acquisition of visual expertise. Crucially, our results will provide insight into whether specific visual expertise elicits by-products for visual perception more broadly, informing existing and future theoretical models of expertise development (e.g. Gegenfurtner et al., 2023; Sheridan & Reingold, 2017).

Method

Participants

Our 'high visual expertise' group consisted of trainee radiologists, reporting radiographers, and certified radiologists (n = 44; female = 22; non-disclosed = 1; M age = 36.01 years, SD = 9.45, M years of professional experience viewing medical images = 12.12 years, SD = 9.20, M medical images per day = 78.88, SD = 175.77). Of these participants, 10 were recruited from the Norwich Radiology Academy, six were recruited from Cumbria University, and 28 were recruited during the European Congress of Radiology. Our control group consisted of psychology undergraduates, radiography students, and medical students (n = 107; Mage = 22.51 years, SD = 7.86; female = 70). Of these participants, 35 were recruited from the University of East Anglia, 50 were recruited from Lancaster University, 12 radiography students from Cumbria University. and 10 medical and radiography students from the European Congress of Radiology. An additional 46 participants who performed below chance level (scores < 3 out of 4) on the control trials for a given illusion (which were designed to detect potential strategy use and lapses in attention) were excluded: 18 psychology undergraduates, 13 medical students, and 15 radiologists and radiographers.

We consider both radiologists and reporting radiographers to be experts in medical image interpretation. Radiologists are practitioners with a medical degree who perform medical image interpretations; reporting radiographers interpret and provide clinical reports on medical images in a similar fashion. Research shows that both radiologists and reporting radiographers have comparable rates for diagnostic accuracy, indicating equivalent levels of visual expertise in the domain of medical image interpretation (e.g., Lauridsen et al., 2013; Morran & WarrenForward, 2016). Compared to radiography students, radiology trainees are all qualified medical doctors choosing to specialise in the field of radiology and performing more medical image interpretations, hence these were included in the expert group. All participants were naive to the study's hypotheses and provided informed consent to partake in this study. All procedures performed in this study were in accordance with the ethical standards of institutional and national research committees – the ethical approval was granted by Lancaster University.

Apparatus and Materials

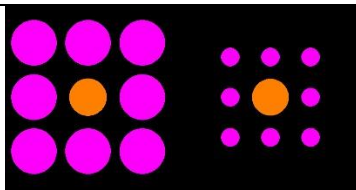
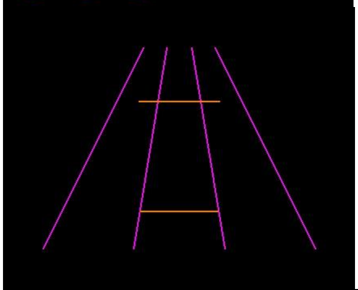
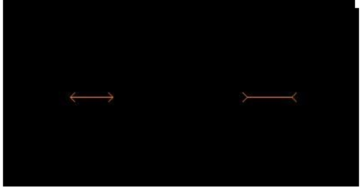
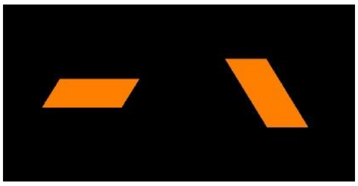
Experts and non-experts were tested on HP Elitebook, HP Omen, and Lenovo ThinkPad laptops with a screen width of 14 inches. The sizing of the illusions on-screen was standardised (i.e., the stimuli were exactly the same dimensions on all laptops and brightness levels were set to maximum on all laptops). The experiment was developed using the computer software EPrime (Psychology Software Tools). Our paradigm was a shortened version of the task developed by Phillips et al. (2004). This task is frequently used to study VI susceptibility across various cultures and populations, including children (e.g., Doherty et al., 2010) and clinical groups (Silverstein et al., 2013)."

The experiment consisted of four geometrical VIs: the Ebbinghaus, Ponzo, MüllerLyer, and Shepard Tabletops illusions (see Table 1 for stimuli examples). The Ponzo, Shepard Tabletops, and Müller-Lyer illusions were developed by Chouinard et al. (2016), while the

Ebbinghaus illusion was developed by our research team. Examples of all illusions are presented in Table 1. For the Ebbinghaus and Ponzo illusions, the target components of the stimuli (i.e., the manipulated parts of the visual illusion) were coloured orange, while the context was purple. The parts of the stimuli that were not manipulated in the geometrical VIs were held at a constant size of 100 pixels. In the Ebbinghaus illusion, the large and small surroundings had diameters of 150 and 50 pixels, respectively. For the Ponzo illusion, two of the converging lines were 420 pixels long and formed a 64-degree angle (outer lines), while the other two were 380 pixels long and had a 10-degree angle (inner lines). The arrowheads in the Müller-Lyer illusion were set at a 45-degree angle. The rhombuses constituting the Shepard Tabletops illusion were 200 pixels long and 100 pixels wide.

Table 1

Visual Illusions Used in the Study

Illusion	Effect	Picture
Ebbinghaus	The central circle surrounded by smaller outer circles is usually perceived as bigger.	
Ponzo	The top line is perceived to be longer despite being the same length as the bottom line.	
Müller-Lyer	The line with the arrowheads pointing outwards is seen as longer than the line with arrowheads pointing inwards.	
Shepard Tabletops	The vertical parallelogram is perceived as longer and broader, despite them both being identical in size.	

Note. Table 1 indicates how the target part of the VIs were manipulated compared to the part that was held constant. For the Ebbinghaus and Müller-Lyer 'geometrical VIs', the manipulation was achieved by physically increasing/decreasing the size of the stimuli.

Procedure

Participants were seated in front of a computer and instructed to keep an upright posture to maintain the same viewing perspective across the whole experiment. The participant's face was roughly 60 cm from the screen, ensured by asking each participant to sit so their stomach was always touching the edge of the desk. Participants were informed that they would be presented with a battery of VIs. They were instructed not to try to 'see through the illusions' and respond based on their first impression as quickly and accurately as they could. Finally, participants were told that if they were unsure about their answer, they should guess. Most participants were seated in a cubicle. Participants recruited during the European Congress of Radiology sat at a table in a corridor, where other members of the congress could freely pass.

Before completing the experiment, participants provided basic demographic data. Each VI had its own unique set of instructions presented on screen. For the Ebbinghaus illusion, participants had to select the larger circle by pressing the corresponding key on the keyboard. For the Ponzo illusion, participants had to select the longer of the two horizontal lines. For the Müller-Lyer illusion, the participant had to choose the longer of the two lines (with the instruction that they should focus on the lines between the arrowheads only). For the Shepard Tabletops illusion, the participant had to choose the wider of the two tables. All illusions except the Ponzo illusion were counterbalanced by reversing the images, so the targets appeared on both sides of the screen. All trials for a given illusion were delivered in a block consecutively in a random order. There were 24 trials per illusion divided into six varying difficulty levels.

One difficulty level served as a control, where the context was designed to be helpful (congruent with the illusory effect). For example, in the context of the Ebbinghaus and the Shepard Tabletop illusions, the ‘perceived as larger’ circle/rhombus was actually 2% larger than the comparison circle/rhombus. For the Ponzo and Müller-Lyer illusions, this difference was 4%. The other five trial types were designed to be misleading, where the difference between the two targets varied by 2%, 6%, 10%, 14%, and 18% for the Ebbinghaus and Shepard Tabletops illusions, or 4%, 12%, 20%, 28%, and 36% for the Ponzo and Müller-Lyer illusions. On each trial, correctly identifying the longer/larger stimuli was scored 1 while identifying the incorrect stimuli was scored 0. Thus, participants could score a maximum of 20 correct answers per illusion (excluding control trials), with higher scores indicating lower susceptibility to VIs.

Analytic Plan and Design

Firstly, the normality of the data set was assessed, and outliers were handled using the winsorising technique (Jose & Winkler, 2008); rather than omitting outliers altogether, they were replaced with the closest non-outlier value from the sample (Dixon, 1960). The method is known for its robustness and simplicity (Jose & Winkler, 2008). The data for each participant were analysed excluding scores from the control condition, which was used to detect lapses in attention and/or strategy use. Response accuracy data were analysed using generalised linear mixed-effects models using the glmer function from the lme4 package in R (Bates et al., 2015). Response was the dependent variable. Lastly, differences in illusion susceptibility scores were assessed via a 2 (group: radiography students vs. psychology students) x 4 (Illusion type: Ebbinghaus, Ponzo, Müller-Lyer, and Shepard Tabletops) repeated measures ANOVA to investigate if there are any pre-existing, superior visual abilities in individuals pursuing careers in medical image interpretation.

Results

Outliers

In the control group, one overall value for the Müller-Lyer illusion was decreased via winsorising from 18 to 15, and two were increased from eight to 10. Following these adjustments, the normality of the data was assessed using the Shapiro-Wilk test across each VI within each of the two groups. These tests indicated normal distribution for three VIs in the expert group ($p > .104$), except for the Müller-Lyer illusion ($p = .007$). For the control group, VIs were not normally distributed ($p < .019$), except the Ponzo illusion ($p = .124$).

Generalised Linear Mixed Effect Models

Stimuli size differences (%) between comparison stimuli were coded as 2, 6, 10, 14, and 18 for the Ebbinghaus and Shepard Tabletops illusions, and 4, 12, 20, 28, and 36 for the

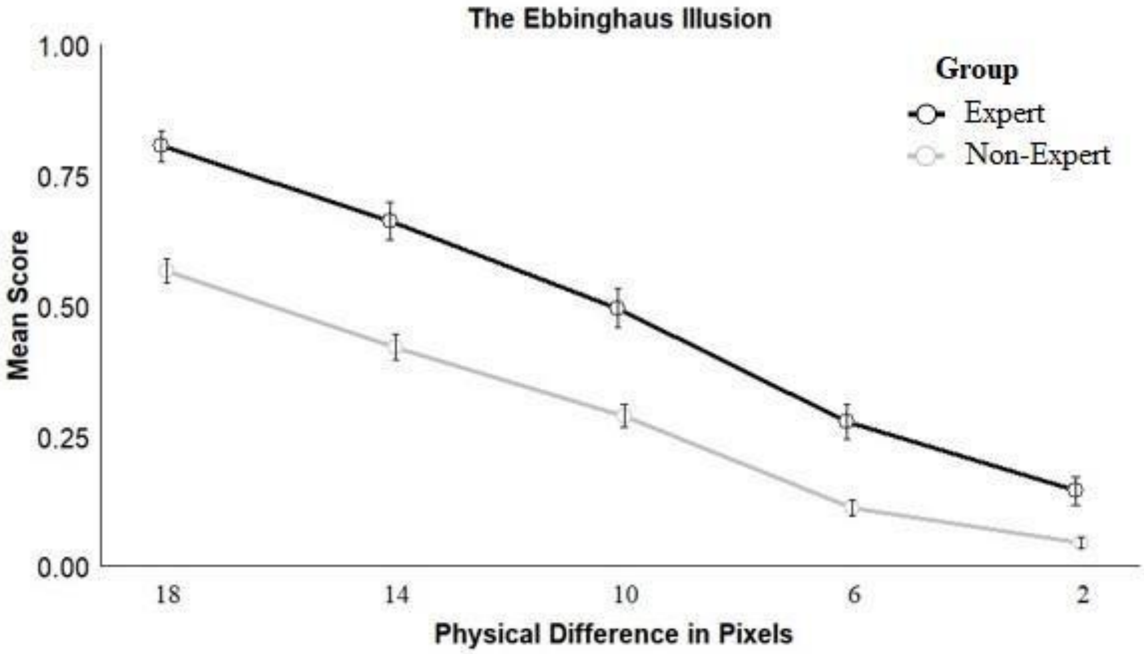
Müller-Lyer and Ponzo illusions. The dependent variable was response accuracy – for each trial per VI the participant could score 0 (incorrect answer) or 1 (correct answer). The likelihood of responding correctly by chance was 50%. The baseline model contained a by-participant random intercept with a random slope of stimuli size difference. Fixed effects of expertise group and stimuli size difference were tested individually, then in combination, and then the interaction between these effects was tested. Each increasingly complex model was compared against the baseline or current best-fitting model to test whether the additional effects significantly improved fit. Once the final model containing experimental variables was established, individual difference measures were added to test whether their inclusion significantly improved fit (age as a numerical value, and sex scored categorically – males were coded as -0.5, while females were coded as 0.5) in the combined population, then years of experience and images per day in the expert group only (also as numerical values). Only the final models are reported below (see Table 2); model-building sequences for each illusion are detailed in the Supplementary Materials.

The Ebbinghaus Illusion

The best-fitting model for the Ebbinghaus illusion included fixed effects of size difference (z = -19.85, p < .001) and group (z = 4.25, p < .001). Across groups, participants were more likely to respond accurately as differences between stimuli increased. Experts (M = 0.49, SD = 0.43) were more likely to respond accurately across difficulty levels than nonexperts (M = 0.29, SD = 0.36; see Figure 1).

Figure 1

Participants' Responses Across Different Conditions for the Ebbinghaus Illusion



Note. The larger the physical difference between the target and the comparison circle, the weaker the illusion.

When exploring the effects of individual differences, the inclusion of sex significantly improved model fit. Across groups, males responded significantly more accurately than females (z = -2.09, p = .037). This replicates previous research on sex differences in susceptibility to the Ebbinghaus illusion (e.g., Phillips et al., 2004). Age was not a significant predictor. For the group with expertise in medical image interpretation, the inclusion of medical images viewed per day or years of experience as fixed effects did not significantly improve model fit.

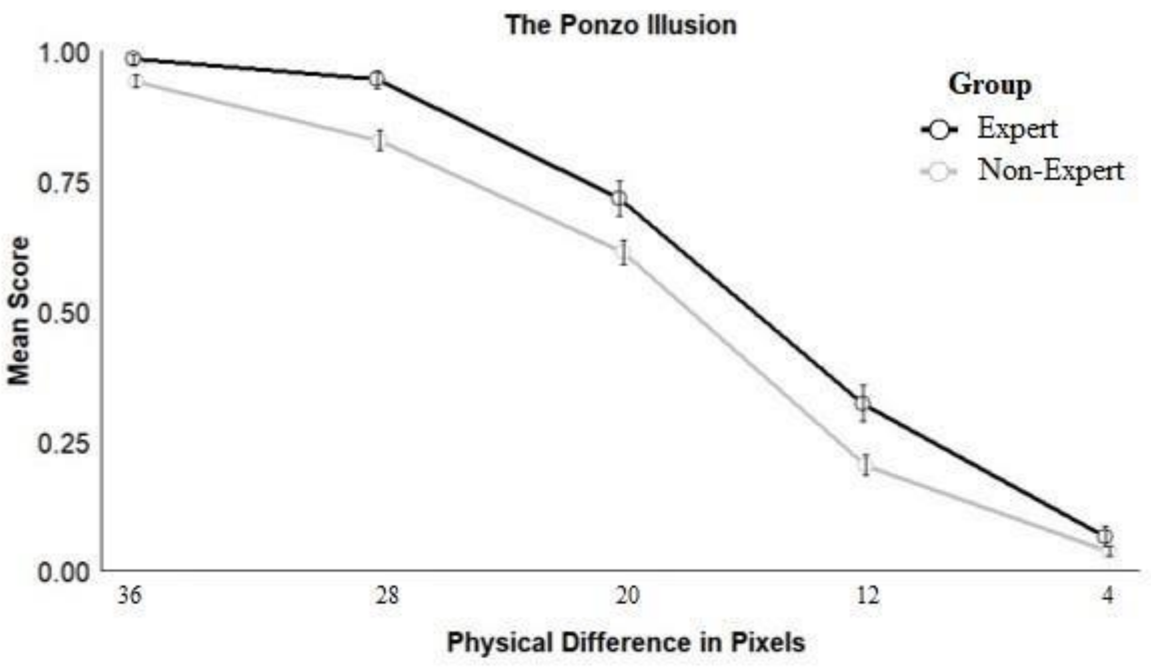
The Ponzo Illusion

The best-fitting model for the Ponzo illusion included fixed effects of size difference (z = 24.60, p < .001) and group (z = 2.54, p = .011). Across groups, participants were more likely to respond accurately as differences between stimuli increased. Experts (M = 0.61, SD = 0.46) were more likely to respond accurately across difficulty levels than non-experts (M = 0.52, SD = 0.47; see Figure 2).

When exploring individual differences, the inclusion of sex significantly improved model fit. Across groups, males responded significantly more accurately than females (z = 2.28, p = .017). This replicates previous research on sex differences in susceptibility to the Ponzo illusion (e.g., Miller, 1999, 2001). Age was not a significant predictor. For the group with expertise in medical image interpretation, the inclusion of medical images viewed per day or years of experience as fixed effects did not significantly improve model fit.

Figure 2

Responses Across Different Conditions for the Ponzo Illusion



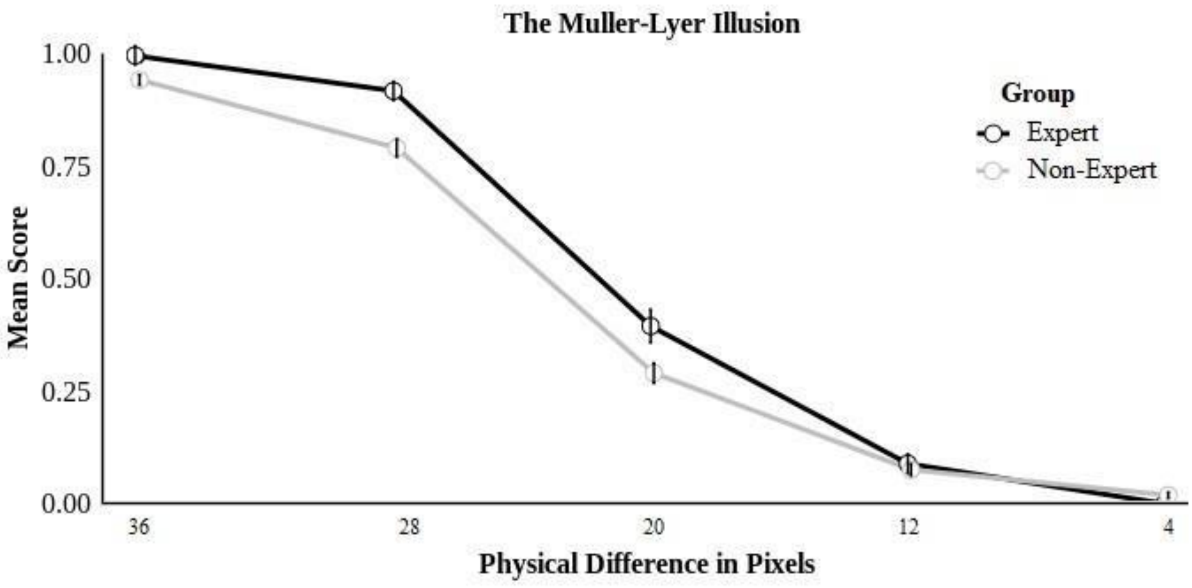
Note. The larger the physical difference between the target and the comparison line, the weaker the illusion.

The Müller-Lyer Illusion

For the Müller-Lyer illusion, the best-fitting model included the group x size difference interaction ($z = -2.90$, $p = .002$; see Figure 3). The interaction was deconstructed by testing the effect of size difference for experts and non-experts separately. The effect of size difference was significant for both the expert ($z = -15.70$, $p < .001$) and non-expert groups ($z = -23.13$, $p < .001$); both groups were more likely to respond correctly as size differences between stimuli increased. We also tested the effect of the group for trials with low (4-20%) and high differences (28-36%) in stimuli size separately. While the groups' response accuracy did not significantly differ when size differences between stimuli were small ($z = 0.02$, $p = .988$), experts ($M = 0.96$, $SD = 0.21$) responded with significantly greater accuracy than non-experts ($M = 0.87$, $SD = 0.34$) when size differences between stimuli were larger ($z = 3.60$, $p < .001$). This suggests that experts were more accurate in their ability to discern the length of the two lines as that difference becomes more evident compared to non-experts. When exploring the effects of individual differences, the inclusion of either sex, age, images viewed per day, or age of expertise did not significantly improve model fit.

Figure 3

The Interaction Across Different Conditions and Group for the Müller-Lyer Illusion



Note. The larger the physical difference between the target and the comparison line, the weaker the illusion.

The Shepard Tabletops Illusion

The final model included the fixed effect of size difference (z = -21.20, p < .001; see Figure 4), indicating that participants were more likely to respond accurately as differences between stimuli increased. When exploring the effects of individual differences, the inclusion of sex, age, or age of expertise did not significantly improve model fit. Including medical images viewed per day improved model fit, however, the effect was not significant (z = -1.44, p = .149).

Figure 4

Responses Across Different Conditions for the Shepard Table Tops Illusion

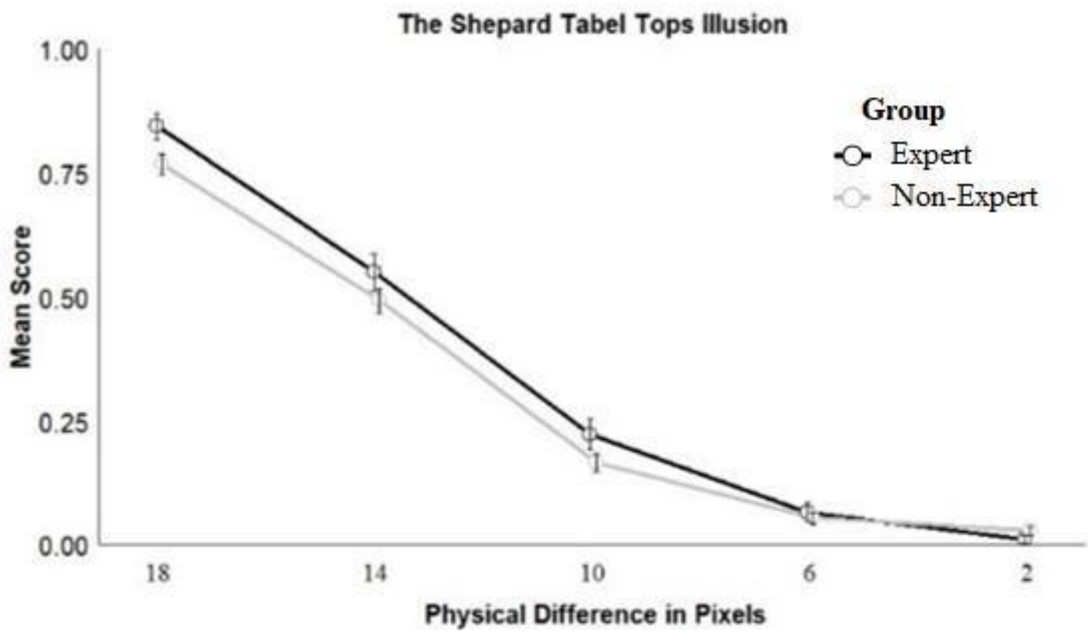


Table 2

Generalised Linear Models for All Four Visual Illusions

Visual Illusion	Fixed Effects	Estimated Coefficient	Standard Error	*z*	Pr(>|z|)
Ebbinghaus	(Intercept)	-4.0	0.2	-17.8	< .001
	Group	1.5	0.4	4.3	< .001
	Difference	-0.3	< 0.1	-19.9	< .001
		AIC	**BIC**	**logLik**	**Deviance**
		2481.5	2517.6	-1234.7	2469.5
	Fixed Effects	**Estimated Coefficient**	**Standard Error**	*z*	**Pr(>|z|)**
Ponzo	(Intercept)	-5.1	0.2	-20.7	< .001
	Group	0.8	0.3	2.5	= .011
	Difference	-0.3	0.1	-24.6	< .001
		AIC	**BIC**	**logLik**	**Deviance**
		2011.9	2048.0	-1000.0	1999.9
	Fixed Effects	**Estimated Coefficient**	**Standard Error**	*z*	**Pr(>|z|)**
Müller-Lyer	(Intercept)	-7.3	0.4	-20.1	< .001
	Group	-1.3	0.7	-1.9	= .069
	Difference	-0.3	< 0.1	-20.9	< .001
	Group x Difference	-0.1	< 0.1	-2.9	= .004
		AIC	**BIC**	**logLik**	**Deviance**
		1863.1	1905.1	-924.5	189.0
	Fixed Effects	**Estimated Coefficient**	**Standard Error**	*z*	**Pr(>|z|)**
Shepard	(Intercept)	-6.3	0.3	-22.8	< .001
	Difference	-0.5	< 0.1	-21.2	< .001
		AIC	**BIC**	**logLik**	**Deviance**
		2209.5	2239.6	-1099.8	2199.5

Note. The larger the physical difference between the target and the comparison rhombus, the weaker the illusion.

Radiography Students Versus Psychology Students

Finally, to show that observed group differences in VI susceptibility are unlikely to be caused by pre-existing superior visual abilities, we compared radiography students (*n* = 12;

*M*age = 31.42, *SD* = 9.56; female = 10) and psychology students (*n* = 12, *M*age = 25.53, *SD* = 11.02, female = 10), who did not differ on age (p = .180). There was a main effect of illusion, $F(3, 66) = 6.27$, $p < .001$, ηp2 = 0.22, but no effect of group, $F(1, 22) = 1.04$, $p = .318$, ηp2 = 0.05, and no interaction, $F(3, 66) = 0.05$, $p = .985$, ηp2 < 0.01. This suggests that our expert sample's reduced susceptibility to VIs in the preceding analyses may be attributable to extensive training and experience, rather than superior perceptual abilities prior to acquiring visual expertise.

Discussion

To discover whether specific visual expertise affords general benefits to visual perception, we investigated whether radiologists and reporting radiographers - professionals with extensive exposure to medical imagery - are less susceptible to basic visual illusions than individuals who lack similar training. Consistent with our hypothesis, experts in medical image interpretation demonstrated reduced susceptibility to the Ebbinghaus, Ponzo, and Müller-Lyer illusions, but not the Shepard Tabletops illusion. As medical radiography students performed similarly to psychology students, it seems unlikely that these differences in VI susceptibility are due to pre-existing visual abilities. These findings present evidence that expertise in perceiving specific kinds of visual stimuli may afford domain-general benefits to visual perception. Our results diverge from previous literature and existing models of perceptual expertise (e.g. Sheridan & Reingold, 2017), which have claimed that proficiency does not transfer beyond the specific domain of expertise.

Our findings challenge existing claims about the domain-specific, or even sub-domain specific, nature of experts' visual abilities in the field of medical image interpretation (e.g., Nodine & Mello-Thoms, 2010; Sheridan & Reingold, 2017). The holistic processing account (Sheridan & Reingold, 2017) posits that an individual's enhanced ability to interpret medical images should not translate into improved performance in other areas. Indeed, experts typically do not outperform laypersons in visual search tasks beyond their area of expertise (for an overview, see Sheridan & Reingold, 2017). However, in contrast to most research within the field of visual expertise, our study did not assess visual search abilities. Instead, we evaluated experts' ability to detect small changes in size within the context of visual illusions. This approach tapped into different perceptual abilities to those involved in visual search tasks, and our findings suggest that expertise in medical image interpretation may improve the ability to disregard irrelevant context and enhance perceptual rescaling abilities. The ability to disregard irrelevant context is crucial for the successful interpretation of medical images (Wolfe et al., 2016), while perceptual rescaling (which causes VIs susceptibility in some illusions) may be required to turn 2D images into 3D representations of the human body, which experts in radiology frequently do (Corry, 2011). Therefore, extensive practice in attending to task relevant areas, combined with turning 2D into 3D, may result in perceptual changes that are transferrable beyond the domain of expertise. Overall, these data are the first to demonstrate that professional visual expertise may induce changes in visual perception that extend beyond a specific domain.

To explain these results, we propose that a stronger local bias is a by-product of extensive visual expertise. Previous studies have shown that radiology experts are quick to fixate on task-relevant areas in medical images, thereby improving the speed at which they detect abnormalities (Sheridan & Reingold, 2017). This efficiency has been linked to memorised representations of target areas (Brams et al., 2020), implicating stronger top-down influences, where previously seen medical images and expectations about the appearance of healthy scans direct attention to relevant areas where abnormalities can be found. However, we argue that this approach could also include a local component – experts may demonstrate the ability to visually disregard irrelevant areas of the image by focusing on local details of the visual scene (Wolfe et al., 2016).

When instructed to discriminate the sizes of two stimuli, our expert sample may have processed context to a lesser extent, thereby reducing the illusory effect and resulting in more accurate estimates. This effect appeared to be particularly evident in the Ebbinghaus illusion, where the illusion-inducing elements are not physically incorporated into the targets (i.e., the inner circles), allowing the context to be visually ignored. The possibility that the observed effect of visual expertise is due to reduction of top-down influences is supported by the fact that VI susceptibility does not rely on previous knowledge (e.g. being told how the VI works, does not remove its effect). Prior research has also demonstrated that experts' eye movement patterns are significantly influenced by local stimulus effects relative to non-experts (Kok et al., 2012), indicating superior ability to focus on areas of interest. Thus, our findings suggest that the role of local biases should be acknowledged and integrated into current theories of perceptual expertise.

One possibility is that top-down influences and a local processing bias develop simultaneously through training the visual system on specific stimuli. As knowledge and target representations (top-down) develop during the acquisition of expertise, the ability to focus on local areas of the image while suppressing irrelevant information also develops, enhancing target detection (van der Gijp et al., 2017; Wolfe et al., 2016). This theory also explains why experts in radiology do not retain their superior visual search abilities outside their area of expertise (like searching for Waldo/Wally character – Nodine & Krupinsky, 1998). Visual search is primarily driven by top-down influences, which do not translate to finding targets beyond one's area of expertise, as mental target representations cannot be applied. This theory requires validation in other domains of visual expertise, such as chess.

Research indicates there is no unique common mechanism underpinning VIs (Cretenoud et al., 2019). With experts showing the strongest reduction in their susceptibility to the Ebbinghaus as compared to the control group (as suggested by the largest estimated coefficient of 1.5 compared to other VIs), it would be logical to look at radiological training for a possible explanation. The Ebbinghaus is an illusion of relative size perception, and an expert is routinely required to comment on the size of image features when writing radiological reports of image findings. These are often objective quantitative measurements of features such as blood vessel diameter, the diameter of a tumour, or size of an acute stroke on a brain scan for example. It is important that these measurements are accurate for diagnostic purposes so all imaging software will include calibrated calipers to ensure accuracy. It is probable that perceptual learning will be happening, as the expert on initial viewing of the image may detect that the size of an organ or blood vessel could be outside the normal range, but they will get instant feedback when they use the software to obtain an accurate measurement. This suggests that advantages in ignoring irrelevant context may develop through profession-specific training.

We observed significant differences between experts and non-experts on three out of four Vis (the Ebbinghaus, Ponzo, and Müller-Lyer illusions), but not the Shepard Tabletops illusion. Unlike the other VIs, the Shepard Tabletops illusion does not present misleading context – its illusory effect comes from differences in orientation of the two rhombuses. Therefore, in line with our hypothesis that experts would show superior ability to ignore irrelevant context, the lack of significant differences between the two groups is unsurprising. With no misleading context to ignore, experts did not benefit from heightened attention to taskrelevant areas. Alternatively, the Shepard Tabletops illusion produced the lowest susceptibility scores of all the illusions tested, perhaps indicating a generally increased difficulty in responding to this illusion. If the difficulty level was decreased (e.g., by increasing the intervals by which the conditions were varied), experts could exhibit reduced susceptibility, in line with the other illusions. This, however, requires further investigation.

Importantly, VI susceptibility did not significantly differ between medical students and non-medical students, nor between radiography and psychology students. This is indirect evidence that individuals who pursue careers in medical image interpretation do not self-select based on inherent visual abilities; instead, these abilities most plausibly develop through practice. Further research is required to elucidate what components of radiology training are responsible for reducing susceptibility to VIs and how much exposure to training is required to elicit changes in perception. Lastly, as reported in previous studies, we observed that susceptibility to the Ebbinghaus and Ponzo illusions is diminished in males (e.g., Miller, 1999; Phillips et al., 2004). This finding suggests that, under specific illusory conditions, context integration may be reduced in males due to possible differences in local processing. Future studies investigate the role of sex differences upon VI susceptibility, as clear evidence on this issue is lacking (Shaqiri et al., 2018).

Future studies should include other groups considered experts in visual perception, such as chess players, as well as conduct comparisons between different sub-domains of radiology expertise. Such investigations would elucidate whether different sub-domains of expertise (e.g., chest imaging versus mammography) and their associated training differentially affect visual perception. It is of particular interest, as Nodine and Mello-Thoms (2010) note that gaining expertise in interpreting chest images does not automatically apply to one's ability to interpret mammograms – suggesting that the ability to interpret medical images is even subdomain-specific.

Conclusion

Our research advances theoretical understanding of how expertise and training impact fundamental mechanisms underpinning visual perception. Current models of visual expertise claim that enhanced top-down influences result from visual training and developing expertise. Focusing on perceptual skills that do not correspond to visual search capabilities, we present evidence that experts may learn to attend to visual scenes locally, thus disregarding irrelevant context. For this reason, some visual skills developed by experts in radiology and radiography appear to be transferrable beyond their domain of expertise.

Chapter VI

Thesis Continuity Statement

Chapter II underscored the potential significance of brain mechanisms in the processing of VIs, suggesting that the developing brain may handle VIs differently. In this chapter, we endeavoured to explore VIs susceptibility within a cohort known to manifest specific brain abnormalities, namely Parkinson's disorder. This group is also recognised for exhibiting anomalous visual perception, as well as exhibits deficits in their perception of depth. Furthermore, this group is also known to experience spontaneous VIs during their everyday lives – objects appear as larger or further way than they actually are, mimicking the effects observed in geometrical VIs. Our aim is to glean insights into the influence of brain function, specifically pathophysiology of the basal ganglia and dopamine deficits, which are core characteristics of Parkinson’s disorder on context integration and pictorial depth perception. The findings of this study will provide insight whether dopamine and basal ganglia could be linked to VI susceptibility, thus providing a better understanding of the visual deficits observed in Parkinson’s disorder. This Chapter has been published in *Frontiers in Psychology*.

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Abstract

Parkinson's disorder (PD) is a common neurodegenerative disorder affecting approximately 1-3% of the population aged 60 years and older. In addition to motor difficulties, PD is also marked by visual disturbances, including depth perception, abnormalities in basal ganglia functioning, and dopamine deficiency. Reduced ability to perceive depth has been linked to an increased risk of falling in this population. The purpose of this paper was to determine whether disturbances in PD patients' visual processing manifest through atypical performance on visual illusion (VI) tasks. This insight will advance understanding of high-level perception in PD, as well as indicate the role of dopamine deficiency and basal ganglia pathophysiology in VIs susceptibility. Groups of 28 PD patients (*Mage* = 63.46, SD = 7.55) and 28 neurotypical controls (*Mage* = 63.18, *SD* = 9.39) matched on age, general cognitive abilities (memory, numeracy, attention, language), and mood responded to Ebbinghaus, Ponzo, and Muller-Lyer illusions in a computer-based task. Our results revealed no reliable differences in VI susceptibility between PD and neurotypical groups. In the early- to mid-stage of PD, abnormalities of the basal ganglia and dopamine deficiency are unlikely to be involved in top-down processing or depth perception, which are both thought to be related to VI susceptibility. Furthermore, depth-related issues experienced by PD patients (e.g., increased risk for falling) may not be subserved by the same cognitive mechanisms as VIs. Further research is needed to investigate if more explicit presentations of illusory depth are affected in PD, which might help to understand the depth processing deficits in PD.

Keywords: Parkinson's disease, visual illusions, Ebbinghaus illusion, Ponzo illusion, Muller-Lyer illusion, depth perception

Susceptibility to Geometrical Visual Illusions in Parkinson's Disorder

Visual illusions (VIs) occur when the configuration of a stimulus causes the viewer to incorrectly perceive relationships between its parts (Notredame et al., 2014). VIs have been widely used as a tool to investigate how visual perception develops (e.g., Doherty et al., 2010) and the impact of neuropsychological disorders such as schizophrenia (for a review see King et al., 2017; Costa et al., 2023) and autism (for a review see Gori et al., 2016). Although impairment of visual perception (e.g., hallucinations) is now well established in Parkinson's disorder (PD) (Nieto-Escamez et al., 2023; Sauerbier and Chaudhuri, 2013; Weil et al., 2016), research has yet to investigate how PD affects susceptibility to VIs. Furthermore, depth perception – which is linked to VI susceptibility (e.g., Doherty et al., 2010; Gregory, 1963, 1966) and increased risk of falling (Cummings et al., 1995) – is shown to be affected in PD (Maschke et al., 2006). Therefore, studying VI susceptibility in this population may indicate how neuropsychological characteristics of PD (e.g., dopamine deficits and the pathophysiology of the basal ganglia) impact depth perception and top-down visual processing.

PD is a common neurodegenerative disorder affecting approximately 1-3% of the population aged 60 years and older (Ball et al., 2019; Pringsheim et al., 2014). It is characterised by motor deficits including tremors, rigidity, bradykinesia (slowed movement execution and initiation), and postural instability (Berardelli et al., 1983; Guttman et al., 2003). Although PD was traditionally considered to be a paradigmatic motor disorder, non-motor disruptions (including visual distortions) are experienced by the majority of PD patients (Chaudhuri et al., 2011). Visual distortions in PD include decreased contrast sensitivity (Sauerbier and Chaudhuri, 2013; Uc et al., 2005; van der Lijn et al., 2022), decreased colour discrimination (Pieri et al., 2000), deficits in motion and spatial perception (Uc et al., 2005), visual acuity deficits (Uc et al., 2005), and visual hallucinations (Barnes and David, 2001; Weil et al., 2016).

It is widely regarded that visual disturbances in PD are caused by a reduction of dopamine (Bodis-Wollner, 1990). Dopamine, a key neurotransmitter in the mammalian brain (Bibb, 2005), is believed to play a crucial role in visual perception (Harris et al., 2003). For example, Andreou and colleagues (2015) showed that dopamine influences neurotypical adults' sensitivity to detecting an object in snowy (noisy) black-and-white pictures. Dopamine has also been shown to influence visual perception in PD. Multiple studies have found that retinal dopamine levels and dopaminergic innervation surrounding the fovea are reduced in PD (Harnois and Di Paolo, 1990; Nieto-Escamez et al., 2023; Sauerbier and Chaudhuri, 2013), resulting in visual perception deficits such as poorer light adaptation and decreased contrast sensitivity (e.g., Armstrong, 2015; Pieri et al., 2000). Other visual deficits that are linked to dopamine deficiency include greater thresholds for motion detection (e.g., Trick et al., 1994), colour discrimination (e.g., Buttner et al., 1994), as well as visuospatial deficits (e.g., Gibson et al., 1987; for an overview of dopamine-related deficits in PD, see Brandies & Yehuda, 2008).

Another hallmark of PD is the pathophysiology of the basal ganglia (Obeso et al., 2000). The basal ganglia are believed to control motor and cognitive functioning (Macpherson & Hikida, 2019); however, recent research has implicated their role in visual perception (Maschke et al., 2006; Nieto-Escamez et al., 2023). Maschke and colleagues (2006) showed that PD patients and patients with spinocerebellar ataxia (a movement disorder) made greater errors when estimating the slant of an illusory display (Ames Trapezoidal Window). The difficulties evidenced by PD patients were attributed to differences in the basal ganglia's functioning. Furthermore, dopamine losses across key components of the basal ganglia (e.g., subthalamic nucleus, substantia nigra, and globus pallidus) are observed in PD (Benazzouz et al., 2014). Dopamine deficiency in the basal ganglia is of particular interest, as the link between these two is thought to be related to the processing of visual information. Sil'kis (2007) proposed a mechanism in which the basal ganglia modulates the efficiency of synaptic transmission in an interconnected parallel circuit that involves the limbic cortex, basal ganglia, thalamus, and cortex. This process is contingent on dopamine-dependent processes. It is, therefore, plausible to suspect that changes to this circuit in PD, could result in abnormal VIs susceptibility.

Given the well-documented abnormalities in depth perception in PD (Maschke et al., 2006; Ou et al., 2018), which could be linked to dopamine deficiency and the role of the basal ganglia (e.g., Maschke et al., 2006), it may be that susceptibility to depth-related VIs (e.g., the Ponzo illusion) is atypical in this population. Studying VIs in PD will enable us to comprehend the potential relationship between dopamine losses and basal ganglia pathophysiology with susceptibility to VIs. Consequently, VIs could offer a promising approach to address perceptual depth deficits in PD.

Although abnormalities in the basal ganglia and deficiency in dopamine levels could potentially influence sensitivity to depth-related VIs in PD, there are reasons to believe that sensitivity to *high-level* VIs may be preserved. The term ‘high-level VIs’ is used to classify illusions that are thought to emerge at a later stage of visual processing (from approximately the V1 and beyond) compared to low-level illusions that are mediated at the retinal level and up to V1 (King et al., 2017). The Ebbinghaus, Ponzo, and Muller-Lyer are examples of high-level illusions, while the Brightness and Herman Grid illusions are examples of low-level illusions (King et al., 2017).

Milner and Goodale’s (1992) classic theory proposes that there are two visual streams in the brain. The ventral stream is responsible for perception for vision, while the dorsal stream is responsible for perception for action. VIs represent a unique method for investigating differences between these two streams. Research shows that even if the Ebbinghaus illusion is perceived, grip aperture is not affected by the illusion in neurotypical adults (e.g., Haffenden et al., 2001). Also, for the Ponzo illusion, it has been shown that grasping in neurotypical adults is not ‘fooled’ by illusory displays (Ozana & Ganel, 2020). Studies on differences in perception and action relating to VIs have been used to demonstrate the dichotomy between dorsal and ventral streams. Research examining the functioning of ventral and dorsal visual streams in PD patients has revealed abnormalities in vision for action in a blind walking task coupled with intact performance on a line matching task (Giovannini et al., 2006). These findings suggest that impairments in visual perception in PD may be explained by abnormalities in dorsal stream processing, while the ventral stream remains unaffected, potentially preserving sensitivity to high-level VIs. In line with these findings, PD patients also experience deficits associated with higher level visual processing of motor actions including slower motor imagery (Poliakoff, 2013) and difficulties observing other people perform actions (Tremblay et al., 2008). These differences in processing visual action signal possible impairments in dorsal stream functioning.

This study is the first to test PD patients on their susceptibility to the Ebbinghaus, Ponzo, and Muller-Lyer illusions using the method of adjustment. PD patients and neurotypical age-matched controls completed a series of online illusion tasks in their own homes. On one hand, based on evidence of depth perception abnormalities in PD (e.g., Ou et al., 2018), we anticipated that PD patients may be less susceptible to these VIs than controls. However, we also believe the differences are likely to be stronger for VIs with most explicit depth, like the Ponzo illusion. However, on the other hand, we recognized that PD patients' susceptibility to these VIs could be unaffected due to a lack of severe disruption to the ventral stream. Our findings will advance theoretical understanding of how PD impacts susceptibility to high-level VIs and ventral stream visual processing.

Method

Participants

Power Analysis

G*Power software (Faul et al., 2007) was used to perform an a priori power analysis to ascertain the necessary sample size required. Power (1- β) was specified as .80 and the significance level (α) was set to .05. The anticipated effect size was modelled on the results obtained by Grzeczkowski et al., (2018). Due to this, we anticipated a medium effect size of $d = 0.46$. For the frequentist parameters defined, a sample size of $N = 56$ is required to achieve a power of .80 at an alpha of .05. Hence, we aimed to recruit 56 participants.

Demographics

Participants included 27 PD patients (15 females, 12 males) and 28 neurotypical participants (17 females, 11 males). PD participants were recruited from the Department of Psychology database of PD patients at Lancaster University, while controls were recruited via convenience sampling ($n = 18$) and sign-ups to the Centre for Aging Research at Lancaster University ($n = 10$). All PD patients were medicated. Participants were predominantly white British ($n = 47$). Participants were largely well-educated, with the majority holding at least an undergraduate degree ($n = 35$). None of the participants reported having a cognitive impairment or any neurological illness. Nine participants reported having a psychiatric illness (anxiety: $n = 5$; 3 in the control group, and depression: $n = 4$; 3 in the control group). Eleven participants reported visual impairments for which they were receiving treatment, including glaucoma ($n = 3$; 1 in the control group), age-related macular degeneration ($n = 2$), double vision ($n = 3$), astigmatism (control group), keratoconus, and short-sightedness (control group; all $n = 1$). All participants confirmed that they had corrected-to-normal vision despite having these conditions, and the aforementioned difficulties did not affect their ability to perceive the VIs. Participants' visual acuity was not assessed as previous research indicates that VIs susceptibility is not related to it (Cretenoud et al., 2021) as well as in PD visual acuity remains largely perseverated (Hunt et al., 1995).

No significant differences between PD patients and neurotypical controls were observed for age (t = 0.05, p = .96), years of formal education (t = 0.21, p = .835), scores for mild cognitive dysfunction (t = -0.706, p = .484), anxiety (t = 0.599, p = .07), and depression (t = 0.15, p = .882). These non-significant group differences indicate that the groups were closely matched (see Table 1 for more details). Full details of the PD patients' cohort are presented in Table 2 below.

Table 1

Means and Standard Deviations for PD Patients and Neurotypical Adults

	Total	Age	Education	Depression	MOCA	Anxiety	Screen Size
PD Patients	27	63.3(7.64)	15.11(4.17)	4.67(2.73)	24.89(2.04)	5.78(3.94)	35.48(9.93)
Neurotypical Adults	28	63.18(9.39)	14.89(3.52)	3.93(2.61)	24.54(2.04)	5.64(2.64)	36.93(4.3)

Note. Higher values for depression and anxiety indicate more severe symptoms. Higher MOCA scores indicate better cognitive functioning. Screen size is reported in centimetres.

Table 2

Characteristics of PD Patients

Participant	Age	Gender	Years since the PD diagnosis	Years since PD onset	LEDD	Last dose	MOCA	HADS-A	HADS-D	Hoehn and Yahr Stage
1	51	Female	3	5	555	204	22	4	1	1
2	62	Female	8	11	760	30	26	11	6	1
3	65	Male	5	5	660	148	25	1	2	0
4	63	Female	5	6	350	180	26	6	7	2
5	57	Female	2	6	375	85	25	15	6	2
6	56	Male	6	8	1000	136	18	3	5	2
7	58	Male	2	3	973	120	26	6	7	1
8	74	Female	4	5	195	2	26	1	1	2
9	59	Male	5	15	220	0	23	2	3	1
10	70	Male	5	7	595	210	25	4	3	1
11	67	Male	5	10	960	720	25	1	5	1
12	67	Male	9	21	N.A.	204	26	3	0	2
13	70	Male	13	30	N.A.	90	26	2	2	2
14	71	Female	3	6	400	230	26	2	1	0
15	59	Male	4	7	590	25	26	4	3	2
16	67	Male	6	10	840	60	27	12	5	1
17	63	Male	4	5	475	240	25	7	6	1
18	59	Female	6	7	362	420	25	14	5	0
19	75	Female	7	7	1680	127	25	5	7	2
20	51	Female	3	5	555	150	24	3	1	1
21	70	Female	11	2	578	0	27	6	3	2
22	57	Female	2	5	300	150	24	8	5	2
23	67	Female	5	6	500	120	26	6	8	1
24	51	Female	1	4	800	210	20	11	8	2
25	59	Female	5	16	355	1440	26	5	9	1
26	81	Female	7	7	640	255	26	8	9	2
27	60	Male	4	6	715	45	26	6	8	3

Note. The time since the last dose is in minutes. HADS-A and HADS-D correspond to anxiety and depression, respectively (described in further detail below). LEDD corresponds to L-dopa equivalent daily dose, which is amongst the most common medication for PD (Julien, 2021). Hoehn and Yahr's scale refers to the severity of symptoms in PD, ranging from 0 (least severe) to 5 (most severe) (MDS, 2008).

Materials

All study stimuli were developed using Unity 3D© Gaming Engine and were visually displayed to participants using the 'screen share' function in Microsoft Teams. The stimuli were modeled on existing work in the field (e.g., Chouinard et al., 2013; Sperandio et al., 2023). These studies were conducted virtually as a precaution to protect both participants and experimenters from COVID-19. Though it may be seen as a potential confound, previous research indicates that online testing yields reliable measurements, however, the effect sizes tend to be smaller (e.g., Chuey et al., 2021; Pallen et al., 2022). As participants viewed the stimuli through screen share on their personal devices, screen size ranged between 23 and 61 inches. An independent samples *t*-test indicated that screen sizes of PD patients (M = 35.48, SD = 10.56) and neurotypical controls (M = 36.93, SD = 4.30) did not significantly differ, $t(53)$ = -0.706, p = .484. Also, no significant correlations were observed between illusion strength and screen size.

Three visual illusions were used: the Ebbinghaus illusion, the Ponzo illusion, and the Muller-Lyer illusion. Participants were required to adjust the size of a line or circle (depending on the illusion) until they perceived it as equivalent in size to the reference stimuli. The size was adjusted using the right and left arrow keys, and trials were progressed using the *ENTER* key. The experimental software obtained a measure of reaction time (ms). RT data was only used to detect skipped trials (responses faster than approximately 5 seconds, which were accompanied by large Z-score values, at least 2 standard deviations (SDs) away from the mean). Average RTs significantly differed between illusions [$F(1.63, 88.05) = 5.37$, p = .006] but not between participant groups [$F(1, 54)$ = 1.12, p = .294]. Planned comparisons using an independent sample t-test, showed differences between RTs for the Ebbinghaus (M = 21.24, SD = 6.11) and the Muller-Lyer (M = 23.87, SD = 9.10) illusions, t = -2.75, p = .014, as well as between the Muller-Lyer (M = 23.87, SD = 9.10) and Ponzo illusions (M = 21.08, SD = 6.01),

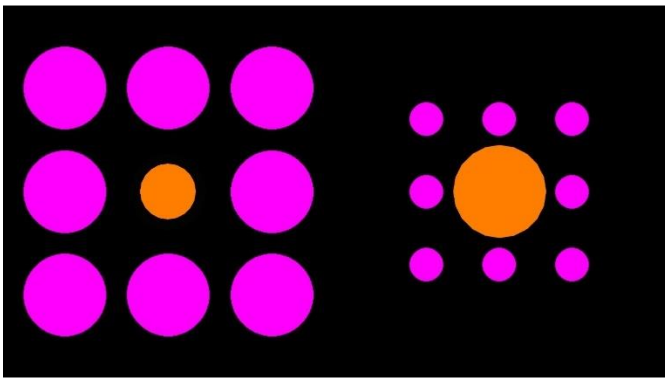
t = 1.92, p = .013. No difference was detected between RTs for the Ebbinghaus and Ponzo illusions; p = .867. Furthermore, we conducted correlations between the illusion's strength and RTs for both groups individually, and the whole sample, to access if prolonged exposure affected VIs susceptibility (Bressan & Kramer, 2021). None of the correlations approached significance.

The Ebbinghaus Illusion

The two orange centre circles were surrounded either by eight pink large inducers (125 pixels in diameter, positioned 35 and 90 pixels away from the central circle) or eight pink small inducers (50 pixels in diameter, positioned 32 and 80 pixels away from the central circle) presented on a black background (see Figure 1). The orange centre circle was 100 pixels in diameter (an example display is illustrated in Figure 1). There were 16 trials in total. The starting size of the adjustable centre circle was 50 pixels in 8 trials and 150 pixels in 8 trials. The side of appearance (left or right) and inducer size (large or small) for the adjustable circle varied between trials, with four trials for each size and side combination. The order of presentation was randomised.

Figure 1

Example Ebbinghaus Illusion Trial



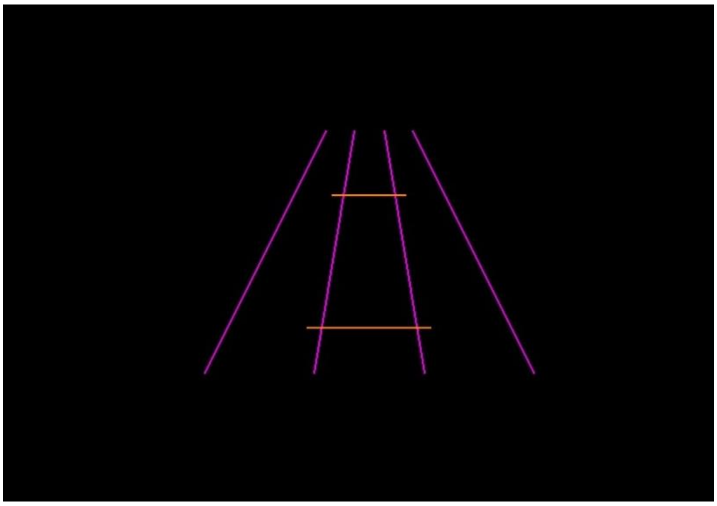
Note. Participants were required to manipulate the size of the right orange circle to match the size of the left orange circle (or vice versa).

The Ponzo Illusion

Four pink converging lines were used as inducers (two at 420 pixels in length at a 64-degree angle, and two at 380 pixels in length at a 10-degree angle). The adjustable and reference horizontal lines were orange and 135 pixels apart. The reference line for both methods of measurement was held constant at 100 pixels. An example display can be found in Figure 2. There were 8 trials in total; in 4 trials the adjustable line started at 50 pixels, and in 4 trials the adjustable line started at 150 pixels. In half of the trials, the adjustable line appeared above the horizontal midline and half below. The order of presentation was randomised.

Figure 2

Example Ponzo Illusion Trial



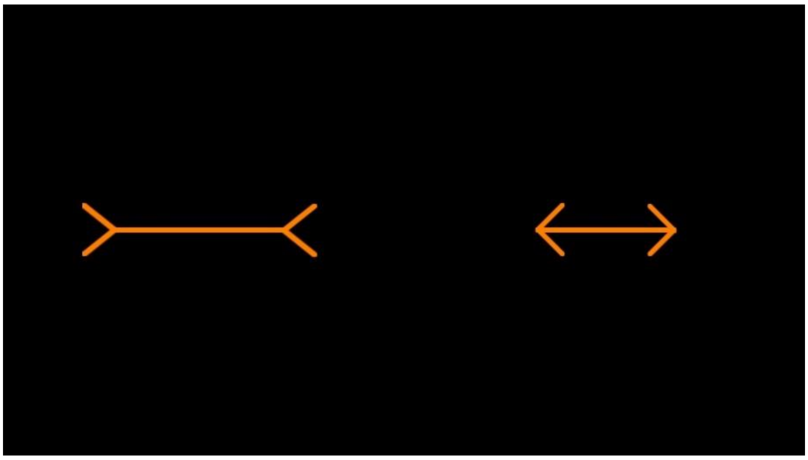
Note. Participants would be required to manipulate the length of the bottom orange line to match the length of the top orange line (or vice versa).

The Muller-Lyer Illusion

Two orange lines with inwards or outwards facing arrows (40 pixels in length) at a 45-degree angle were presented. The reference line for both methods of measurement was held constant at 150 pixels. An example display can be found in Figure 3. There were 16 trials in total with four trials for each side of the presentation (left or right) and arrow type (inwards or outwards facing) combination. The starting size of the adjustable line was 75 pixels in 8 trials and 225 pixels in 8 trials. The order of presentation was randomised.

Figure 3

Example Muller-Lyer Illusion Trial



Note. Participants would be required to manipulate the left orange line (between the arrowheads) to match the length of the right orange line (between the arrowheads), or vice versa.

Questionnaires and Screening Tools

Questionnaires and screening tools were administered to participants via an online interview. These included the Hospital Anxiety and Depression Scale (HADS; Snaith, 2003), the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005), and the Movement Disorder Society – Unified Parkinson Disease Rating Scale (MDS-UPDRS; Goetz, 2007). These measures were included to test whether potential differences in susceptibility to VIs were influenced by participants' cognitive abilities and/or mood.

HADS consists of 14 statements that measure traits of depression (7 items) and anxiety (7 items). Each statement has four corresponding answers which the interviewee can choose between. For example, for the statement 'I feel tense or wound up' (an anxiety item), the response options are: 'most of the time' (3 points), 'a lot of the time' (2 points), 'from time to time, occasionally' (1 point), and 'not at all' (0 points). Higher scores indicate more severe symptomology. During the interview, the participant was instructed to think about their feelings over the past week. The statements were read out loud, followed by the answers, and then the participant chose one of them. If they were unsure, the interviewee was asked to make their best guess. For half of the questions the response options were read in order from negative to positive, and for the other half the response options were read in order from positive to negative.

The MOCA includes 13 tasks measuring a variety of cognitive functions, including visuospatial/executive functions, naming, memory, attention, language, abstraction, delayed recall, and orientation. As the study was conducted online, small changes were implemented. The first part of the visuospatial/executive task (connecting numbered dots) was omitted as the participant was unable to respond due to online administration. Also, in the orientation task, participants were not asked about their present location as the researchers were unable to validate their responses. The participant could therefore score up to 27 points (30 points originally).

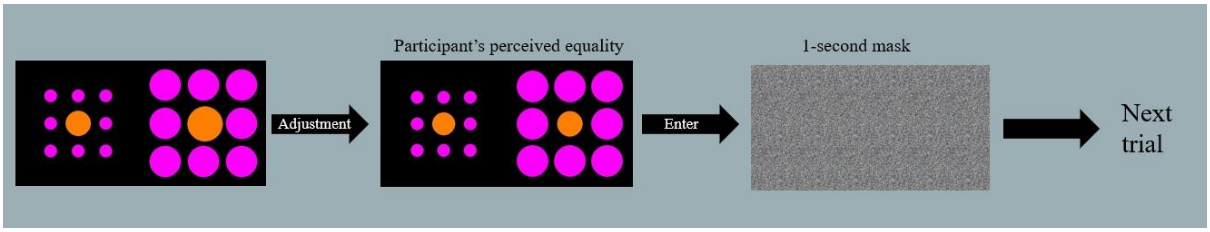
The MDS-UPDRS consists of four subscales measuring: I – non-motor aspects of experiences of daily living (1.1 – 1.6), (questions 1.7 to 1.13 were excluded as they were unrelated to our study's objective); II – motor aspects of experiences of daily living (2.1 – 2.13); III – motor examinations (3.1 – 3.8; 3.15 – 3.18) (questions 3.9 to 3.14 were dropped as the study's online nature prevented the researchers from correctly assessing the participant's performance); IV – motor complications (4.1 – 4.6). Parts I, II, and IV included questions asking participants to rate their difficulty engaging with a variety of daily tasks (e.g., getting dressed and getting out of a deep chair) from normal to severe on a five-point scale. Part III involved a motor examination of the participants, who performed tasks as they were described by the researcher (e.g., holding their hands still in front of them). The researcher then scored the performed action according to the MDS-UPDRS guidelines.

Procedure

All participants were tested online via Microsoft Teams. Before taking part in the online session, participants were required to complete a survey requesting basic demographic information (e.g., age and gender), history of PD and diagnosis, and current medication intake. Then, all participants were screened for mild cognitive impairment (MOCA) and mood disorders (HADS). Individuals with PD symptoms were also assessed using the MDS-UPDRS. Participants were then given control over the researcher's laptop using the Teams share function [which was not possible in some cases (< 5), participants were asked to provide oral instructions to the researcher, however, our RT correlations with VIs susceptibility failed to reach significance, hence the different modes of entering data were not deemed problematic]. Once control was given, participants were presented with the experimental stimuli and asked to manipulate the size of a line (Müller-Lyer or Ponzo display) or centre circle (Ebbinghaus display; either to increase or decrease) using the right and left (left to decrease, right to increase) arrow keys (see Figure 4). Once the participant believed that their stimulus matched the size of the reference non-adjusted line or circle, they were prompted to press *Enter*. If the participant was unable to take control, they were asked to orally instruct the researcher to either increase or decrease the sizes until they were happy with it. Participants were prompted to be as accurate as possible in their judgements and instructed to make their judgements as quickly as possible. In both scenarios, the researcher looked away from the screen to prevent the participant from feeling pressured to respond quickly or to prevent any gaze cues. The order of illusion blocks and trials within blocks were randomised. Once the experiment finished, participants were fully debriefed and encouraged to ask questions. The study took between 45 to 60 minutes to complete.

Figure 4

Example Trial



Note. During adjustment, the participant used the arrows on their keyboard to match the larger of the two orange, inner circles with the other, target circle. Once they perceived the circles as equal in size, they pressed enter to proceed to the next trial.

Analysis Plan

The data were screened to assess for normality of distribution. The magnitude of the illusion was calculated as the difference between the actual size of the target and the participant's response. A 2 (Group: PD patients, neurotypical controls) x 3 (Illusion: Ebbinghaus, Ponzo, and Muller-Lyer) repeated measures ANOVA was conducted. Correlations between VIs, demographic data, and Parkinsonian symptoms were computed using both frequentist and Bayesian analyses. Multiple comparisons were analysed with Holm correction (e.g., Grzeczkowski et al., 2018). Screening analyses were performed using IBM SPSS Statistics (Version 27) and all the remaining analyses were performed in JASP Team (2022).

Results

Normality of The Data Set

Each participant's data were screened for outliers (40 responses per participant) located at least two SDs away from the response mean (unusually low or high values reported) and compared against the population's mean for each particular illusion. Outliers were screened for PD patients and neurotypical adults separately. To ensure consistency across responses, all individual outliers were replaced with a second value for the same trial type.

Several outliers were identified across the data. For the Ebbinghaus illusion, there were 27 outliers (3.01%) out of 896 trials, including 18 in the PD group (16 belonged to one participant, meaning every single trial of that participant was outside -/+ 2 SDs away from the mean, resulting in the exclusion of this participant) and 9 in the neurotypical group. For the Ponzo illusion, there were 20 outliers (4.46%) out of 448 trials, including 14 in the PD group and 6 in the neurotypical group. For the Muller-Lyer illusion, there were 31 outliers (3.45%) out of 896 trials, including 18 in the PD group and 13 in the neurotypical group. The majority of outliers were due to the participant pressing the *enter* key too forcefully, which resulted in skipping a trial (this was identified by unusually quick reaction times of less than 3 seconds). These scores were replaced with the participant's second score in the same condition.

Group Differences Between PD Patients and Neurotypical Controls

To examine differences between PD patients and neurotypical participants on their susceptibility to the Ebbinghaus, Ponzo, and Muller-Lyer illusions, a 2 x 3 repeated measures ANOVA was conducted. Both Levene's test for equality of variance for all three illusions and Mauchly's W test of sphericity indicated that the assumptions for a two-way ANOVA were met; $p = .349$, $p = .777$, $p = .663$, and $p = .057$ respectively. The results revealed a significant effect of the illusion, $F(2, 108) = 628.63$, $p < .001$, $\eta^2 = .87$. The difference between PD patients and neurotypical approached significance, $F(1, 54) = 3.79$, $p = .057$, $\eta^2 = .003$, as did the Population x Illusion interaction $F(2, 54) = 3.07$, $p = .050$, $\eta^2 = .004$. Given our a priori predictions, we proceeded to conduct post-hoc comparisons though note that these should be treated with caution as the interaction was only marginally significant. Post-hoc comparisons using Holm correction (after Grzeczkowski et al., 2017) showed that PD patients were significantly less susceptible ($M = -0.18$, $SD = 0.08$) than controls ($M = -0.23$, $SD = 0.09$) to the Ponzo illusion; $t(54) = 2.19$, $p = .033$, $d = 0.59$. No significant differences were observed for the Ebbinghaus (PD; M = -0.14, SD = 0.04 and controls; M = -0.13, SD = 0.05) and Muller-Lyer illusions (PD; M = -0.54, SD = 0.07 and controls; M = -0.57, SD = 0.08).

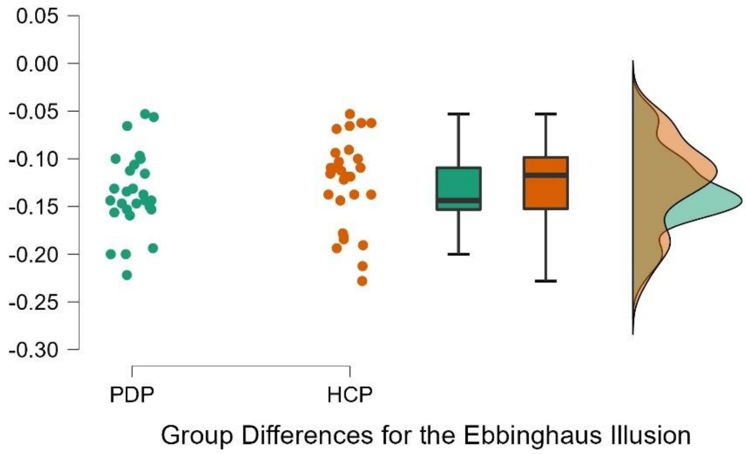
Similar results were observed by conducting a Bayesian 2 x 3 repeated measures ANOVA. Based on Jeffreys' (1939) rule of thumb for interpreting Bayesian results (1-3, 3-10, and 10+, are considered weak, moderate, and strong effects, respectively), we observed weak evidence for an effect of VIs (BF = 0.89), very weak evidence for an effect of group (BF < 0.001), and weak evidence for an interaction (BF = 0.681). Bayesian t-tests yielded similar results for differences between the groups on each VIs. Weak evidence was observed for group differences on the Ebbinghaus, Ponzo, and Muller Lyer illusions; B = 0.399, B = 1.911, and B = 0.67, respectively. Evidence from these Bayesian analyses indicates a lack of differences between PD patients and neurotypical controls on the three tested illusions.

Correlations

Several correlations were performed to assess whether severity of PD symptoms was associated with differences in susceptibility to VIs. The variables of interest included susceptibility scores for each illusion, time since the last medication dose, years since PD diagnosis, years since starting medication, years since symptom onset, LEDD score, and the total MDS-UPDRS score. As some variables were not normally distributed, Spearman's correlations and their Bayes equivalent were conducted. No frequentist or Bayesian correlations approached significance, indicating that susceptibility to VIs was not correlated with patients' PD characteristics.

Figure 5

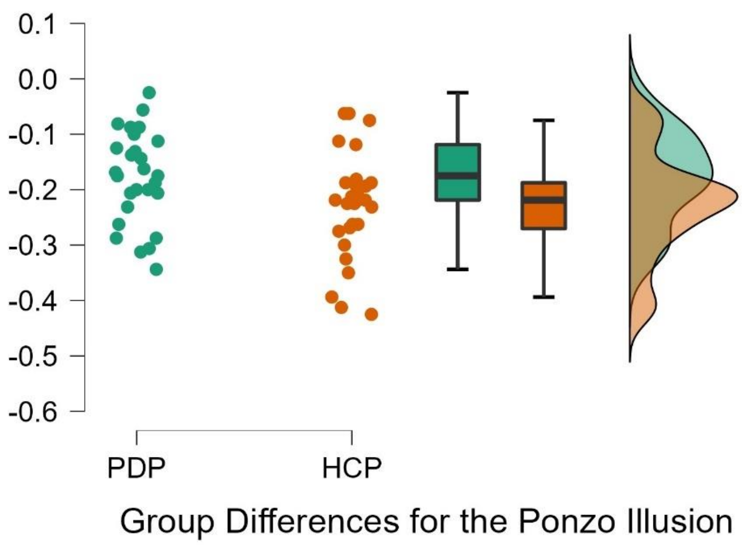
Individual Data Points for the Ebbinghaus Illusion for PD Patients (PDP) and Healthy Control Participants (HCP)



Note. Both groups show overlapping similarities in their susceptibility to the Ebbinghaus illusion.

Figure 6

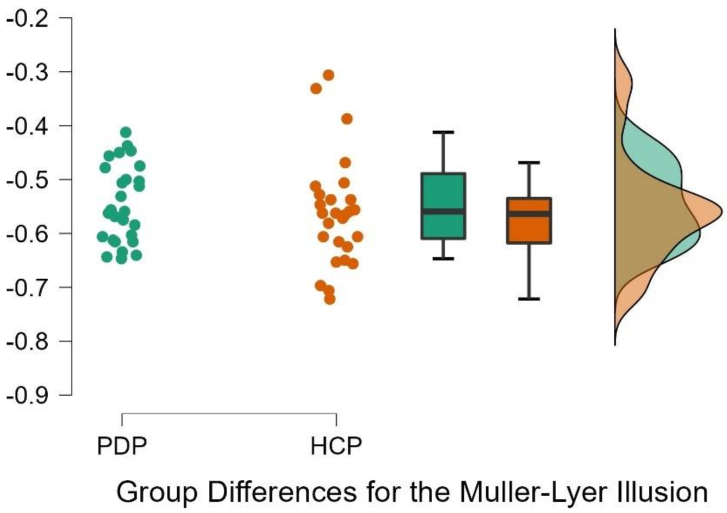
Individual Data Points for the Ponzo Illusion for PD Patients (PDP) and Healthy Control Participants (HCP)



Note. Both groups show overlapping similarities in their susceptibility to the Ponzo illusion.

Figure 7

Individual Data Points for the Muller-Lyer Illusion for PD Patients (PDP) and Healthy Control Participants (HCP)



Note. Both groups show overlapping similarities in their susceptibility to the Muller-Lyer illusion.

Discussion

This study investigated whether PD patients – a population characterised by basic and complex visual disturbances (e.g., Maschke et al., 2006) – and neurotypical adults differ in their susceptibility to the Ebbinghaus, Ponzo, and Muller-Lyer visual illusions. We formulated two competing hypotheses: (a) PD patients may be less susceptible to VIs than neurotypical adults due to abnormalities in the basal ganglia and dopamine deficits affecting their visual processing, or (b) sensitivity to VIs may not be impacted by PD due to their visual deficits specifically affecting dorsal stream processing of actions. Our analyses did not identify robust differences between the two populations' responses for any illusion. These results suggest that dopamine deficiency and basal ganglia pathophysiology may not be directly related to VI susceptibility and that these may affect different aspects of visual perception (Maschke et al., 2006). Furthermore, our data imply that the ventral stream's processing of vision for perception in PD is largely free from pathology when viewing VIs.

Previous research has shown that depth perception deteriorates in older adults (Salonen and Kivela, 2012) and that the inability to perceive depth correctly increases their risk of falls (Cummings et al., 1995; Ivers et al., 2000; Lord and Dayhew, 2001). There is also an extensive body of evidence documenting abnormal depth perception in PD (e.g., Ou et al., 2018), including in illusory contexts (Maschke et al., 2006). Our analysis, however, showed only marginal evidence for abnormal depth perception. PD patients appeared to have reduced susceptibility to the Ponzo illusion. The Ponzo illusion is considered a classic example of a depth illusion (Gregory, 1963), and creates the most apparent experience of depth among the tested illusions. These findings suggest that dopamine deficiency and/or pathophysiology of the basal ganglia may, marginally, affect depth perception as shown by the illusory depth in the Ponzo illusion, adding to already existing evidence concerning such deficits (e.g., Maschke et al., 2006). It is, however, important to note that the depth here is only illusory (induced), and arguably less apparent compared to the Ames Window illusion (such as in Maschke et al., 2006), and it is not real, 3D depth. PD patients might still have difficulties in perceiving depth in everyday situations (e.g., Cummings et al., 1995). Potentially, only a slight indication of reduced susceptibility was observed because PD participants in this study were mostly in the early- and mid-stages of PD. Therefore, it might still be possible that susceptibility to VIs starts deteriorating as PD develops, as other aspects of vision like colour and contrast discrimination abilities get progressively worse (Diederich et al., 2002).

Reduced ability to interpret and process depth cues may result in abnormal susceptibility to the Ponzo illusion. Thus, an incorrect perception of an object's position in the world (whether it appears as closer/further away than it is), could contribute to the increased risks of falls in the elderly. In line with this assumption, many PD patients are shown to exhibit difficulties in perceiving depth, experiencing both teleopsia (objects appear to be further away than they are) and pelopsia (objects appear to be closer than they are; Sasaki et al., 2022).

Furthermore, it is unlikely that these differences observed between PD patients and controls arise due to the abnormal role of top-down influences in susceptibility to the Ponzo illusion, as such a deficit should also be observed for the Ebbinghaus illusion, which is considered a context sensitivity illusion (Kaldy and Kovacs, 2003).

The Ebbinghaus illusion arises due to the perceptual system's top-down integration of display elements (Kaldy and Kovacs, 2003). Our data show that susceptibility to the Ebbinghaus illusion is not significantly different in PD, indicating typical abilities to integrate context in this population. This finding aligns with previous research reporting intact top-down influences on PD patients' responses in visual priming tasks (Straughan et al., 2016) and visual search tasks (Horowitz et al., 2006). By contrast, Mannan and colleagues (2008) found that PD patients were impaired in visual search tasks involving highly salient targets, indicating difficulties with bottom-up processing. The illusions tested in this study belong to a category of high-level VIs that rely on complex cognitive processing and top-down mechanisms, whereas low-level VIs (e.g., the Brightness illusion) are mediated at the level of the retina and bottom-up perception (King et al., 2017). While PD may not impact top-down processing involved in experiencing complex VIs, deficiency of retinal dopamine may result in abnormal susceptibility to low-level VIs. As deficiency in retinal dopamine results in a diminished ability to differentiate contrast (as in colour, e.g., Pieri et al., 2000; Price et al., 1992), PD patients could have higher thresholds in matching colour in Brightness or Adelson's Checkerboard illusions. Therefore, we recommend that future research investigates whether susceptibility to low-level VIs is affected by PD.

Our findings suggest that the pathophysiology of the basal ganglia and dopamine deficits may not affect PD patients' sensitivity to the Muller-Lyer illusion. Therefore, illusions such as the Ebbinghaus and Muller-Lyer may be subserved by neural mechanisms that are largely free from pathophysiology in PD, such as those located in the visual cortex (Cheng et al., 2011; King et al., 2017). The Muller-Lyer illusion is considered to rely on depth cues (Gregory, 1966), just like the Ponzo illusion, which is considered a classic example of a depth illusion (Gregory, 1963). Therefore, the inability to perceive depth cannot be a major factor driving the illusion, at least in the version used here. In line, with Doherty and colleagues' (2010) claims that subtle depth cues are likely to play a part in susceptibility to the Ebbinghaus illusion, the depth cues in the Muller-Lyer illusion are also subtle, hence no differences in susceptibility to those two illusions might have been observed. Thus, the pathophysiology of the basal ganglia and/or dopamine deficits might only be related to more explicit perceptions of depth, and are not directly linked with susceptibility to the Muller-Lyer illusion.

Overall, our observed results support the alternative hypothesis that susceptibility to VIs is largely unaffected in PD patients due to their visual perception difficulties originating from abnormalities in dorsal stream functioning, rather than ventral stream functioning. PD patients showed similar susceptibility to the Ebbinghaus and Muller-Lyer illusions and only marginal evidence for reduced susceptibility to the Ponzo illusion was observed. From this, we conclude that perception of depth is more crucial for executing motor actions than the integration of context. This is, in line with findings by Giovannini and colleagues (2006) who observed that PD patients display abnormalities in their vision for action in a blind walking task, but not a line-matching task. Arguably, the line-matching task does not rely on depth integration, therefore PD patients performed similarly to controls.

Extending this line of research to grasping behaviour, which is guided by the dorsal stream, would potentially provide valuable insight into differences between the dorsal and ventral streams in PD. Previous findings on the dichotomy between the two streams have largely focused on whether individual illusory effects are larger on the ventral stream than the dorsal stream. Here, testing PD patients would allow for a different perspective; one would still assume that the perceptual stream is affected by the illusion in both PD patients and healthy controls, but the action stream is affected by the illusion only in PD patients.

This study has several limitations. Firstly, we did not directly assess our participants' dopamine levels or pathophysiology of the basal ganglia. In line with other studies in the field (e.g., Maschke et al., 2006), our target population was selected based on robust pre-existing knowledge that PD is characterised by dopamine loss and basal ganglia pathophysiology which are known to adversely affect visual perception. Therefore, our conclusions that dopamine loss and the pathophysiology of the basal ganglia do not influence susceptibility to high-level VIs should be interpreted with caution. Furthermore, the online administration of the study resulted in several potential shortcomings. First, varying Internet speed could cause a lag in the delivery of the experiment, impacting the smoothness of the increase/decrease of the targets which the experimenter could not control for. Secondly, although participants were frequently reminded to rely on their visual perception alone, the experimenter could not verify whether the participants truly did so. Finally, our study did not check for the presence of everyday VIs (that are similar to geometrical VIs, but they occur during everyday activities of the patients), that recently gained interest in medical research on PD (Nishio et al., 2018; Sasaki et al., 2022).

In conclusion, our findings suggest that PD patients and neurotypical controls do not differ in their susceptibility to the Ebbinghaus, Ponzo, and Muller-Lyer illusions. The lack of differences was especially evident in the Ebbinghaus and Muller-Lyer illusions that more strongly rely on context sensitivity rather than depth perception. Only a marginal indication of abnormalities in depth perception was indicated by reduced susceptibility to the Ponzo illusion, which compared to the other VIs is a classical illusion of depth. Collectively, our data suggest that context integration, a key component of VIs susceptibility, remains unaffected in the early to mid-stage of PD. Furthermore, our findings suggest that visual deficits in PD are more likely to be related to the dorsal visual stream. This study makes a novel contribution to a growing literature exploring visual deficits in PD and advances the understanding of how visual perception may be affected by dopamine deficiency and abnormalities in the basal ganglia.

Acknowledgments

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Chapter VII

General Discussion

Summary of Findings

Chapter II presents the first up-to-date systematic review examining developmental changes in susceptibility to five geometrical VIs. Its principal findings indicate that when employing forced-choice paradigms, there is often a decrease in the magnitude of a VI observed at a young age. However, when adjusting methodologies are employed, findings tend to either show no differences or reduced susceptibility to the illusion with age. An exception to this pattern is noted with the Muller-Lyer illusion, which consistently exhibits a decreasing trend in magnitude with increasing age across methodologies. The Ebbinghaus and Ponzo illusions showed a largely increasing magnitude with age, while the Poggendorff and Vertical-Horizontal illusions showed a decrease with age. The chapter further delves into the role of different stimuli utilised and the generalisability of findings beyond specific versions of the illusions under study. Furthermore, the shortcomings of previous research and potential confounds served as a guide in selection of additional topics in this doctoral thesis.

Chapter III investigates the susceptibility of children compared to adults concerning the Ebbinghaus illusion, employing two different methods: 2AFC following Phillips et al. (2004) and MOA. Surprisingly, no significant differences in susceptibility were found between children and adults across the two methods. Previous studies using the 2AFC method have found children to be more accurate in their size estimations (e.g., Doherty et al. 2010), which was linked to reduced context sensitivity (Kaldy & Kovacs, 2003). The lack of a significant trend observed with the 2AFC method was attributed to the fact that the children tested have mainly not failed the attention checks, which indicated good engagement with the task – unlike other studies, such as Doherty et al. (2010). In line with our prediction, the MOA task showed no significant difference between children and adults. It is suggested that this method is cognitively more demanding, as it requires the participant to increase or decrease the target, resulting in older participants performing more manipulations in order to find the best match, while children accept the closest possible match – both of which result in similar illusion's magnitude. Collectively, these findings suggested that the ability to visually integrate context and perceive pictorial depth perception is already developed at the age of five.

In Chapter IV, comparisons between VI response methodologies are extended to focus on sex as a differentiating factor. While susceptibility to VIs remains stable across sexes in adult samples, certain methodologies do indicate sex differences. Using 2AFC following Phillips et al., 2004 (which has also replicated their findings), it was shown that males are less susceptible with their susceptibility scores being positively correlated with longer exposure time (thus confirming findings by Bressan and Kramer, 2021). Time, however, was not significantly correlated with any other method nor the Muller-Lyer illusion. Collectively, these findings suggest that certain methods are sensitive to time-accuracy trade-off. Additionally, using MOA in studying the Muller-Lyer illusion results in a doubling of the perceived magnitude of the illusion compared to using 2AFC without randomisation. This suggests different decisional strategies taking place when responding to the same illusion across two different modes of response.

Chapter V introduces the concept of visual expertise to VI research. Through a study involving individuals possessing specific visual expertise developed through professional training - trainee radiologists, reporting radiographers, and certified radiologists - it is demonstrated that visual expertise and frequent translation of 2D images into 3D images likely lead to reduced susceptibility to VIs. This opens an intriguing avenue for investigating the role of visual expertise in susceptibility to VIs. This finding suggests that excessive visual training does not only lead to changes at the global level but also those perceptual abilities at a local level (e.g., the ability to visually attend to only task-relevant, local stimulus) improve as a result of such expertise. Furthermore, it appears that perceptual benefits of domain-specific visual expertise extend to general visual processing abilities as well.

Finally, Chapter VI explores the potential impact of physiopathology, such as basal ganglia function and dopamine deficiency, both of which are frequent in PD patients, on pictorial depth perception. It is observed that individuals with Parkinson's disease exhibit marginally reduced susceptibility to the Ponzo illusion, indicating an influence of these physiological factors on perceptual phenomena. However, due to its marginal significance it should be treated with caution.

Collectively these results indicate that VIs can be successfully used as a measure of top-down and bottom-up influences and pictorial depth perception across a wide range of different populations (e.g., children, adults, radiologists, patients with PD), producing important insight into how VIs are processed in the human perceptual system. Therefore, the theoretical contributions of this thesis allow us to infer that VI susceptibility in specific populations (e.g., PD patients) may or may not be related to specific regions of the brain (e.g., basal ganglia). Furthermore, it allows to investigate how aspects such as development or visual expertise affect the observed magnitude of different VIs.

VIs Across Lifespan

The results of the systematic review, as well as Chapter III, suggest that children's susceptibility to some VIs may be influenced more by cognitive strategies rather than pure visual discrimination, at least for certain VIs and/or response methods. Piaget's (1963) attempt at classifying the susceptibility trends to VIs across development suggested that VIs can be understood as either primary or secondary illusions. The former are decreasing in their magnitude with age, while the latter are increasing. He suggested that this is because children explore primary VIs more systematically, and with the development, they make more eye movements resulting in a decrease with age. Piaget further hypothesized that with the development of depth perception and the ability to perceive perspective, secondary illusions, which tend to increase with age, would decrease during adolescence or adulthood. The dichotomy proposed by Piaget was largely supported by the findings of the systematic review from Chapter II, as the Ebbinghaus and Ponzo illusions were shown to produce largely an increasing trend, while the Muller-Lyer, Poggendorff, and Vertical-Horizontal illusions were shown to have an opposite susceptibility trend. However, the findings of Chapter III would indicate that already at the age of five, the magnitude of the Ebbinghaus illusion is at an adult-like level, therefore the initial increase in susceptibility as predicted by Piaget should happen before the age of five, when the cognitive abilities linked to the Ebbinghaus susceptibility (also see Doherty et al., 2010) are still less developed. Future studies should test Piaget's theory by investigating the Ebbinghaus illusion in a sample of younger children.

The findings of the systematic review also align with an alternative classification of VIs proposed by Ben-Shalom and Ganel (2012). They suggest that VIs can be categorised into two groups based on their physical elements: within-context illusions, such as the Müller-Lyer illusion, where the elements are bound together, and between-object illusions, like the Ponzo or Ebbinghaus illusions, where the elements are physically separated. Ben-Shalom and Ganel (2012) found that both within- and between-object illusions are equally influenced by visual working memory, while iconic memory is unaffected by within-object illusions. Based on these findings, Chouinard and colleagues (2013) proposed that within-object VIs may require more cognitive effort compared to those that involve the binding of local elements (between-object VIs). The theories of Piaget (1963) and Ben-Shalom and Ganel (2012) complement each other. Piaget's idea of centrations in relation to susceptibility to VIs is particularly relevant here. Centration occurs when an object situated at the centre of the visual field is overestimated in comparison to its surroundings (Piaget, 1961, 1963, as cited in Cretenoud et al., 2020). Since primary illusions depend on the interaction of elements within a single fixation (Flavell, 1963, as cited in Hanley & Zerbolio, 1965), these illusions arise due to the simultaneous comparison of these elements (Clem & Pollack, 1975). As a result, children may visually explore type I illusions more, making more centrations than they do with type II illusions, where they may focus on the targets regardless of their surroundings. Although no increasing trend was observed in Chapter III, it is likely that children under the age of five are less susceptible to the Ebbinghaus illusion due to making fewer centrations. Future research should further explore whether within- and between-object illusions are processed by different mechanisms in the brain, and whether these types of illusions are explored differently visually.

Alternatively, susceptibility to the Muller-Lyer illusion may not rely on the integration of local elements but could be attributed to an inappropriate probabilistic strategy employed by children. Howe and Purves (2005a) argue that the illusory effect of the Muller-Lyer illusion arises from the "statistical relationships of the stimulus elements and their possible physical sources" (p. 1237). Due to the conflation of physical properties, such as size, distance, and orientation, in the retinal image, the accurate derivation of real-world sources of the stimulus' properties is compromised (Howe & Purves, 2005b). This discrepancy may lead to an inaccurate perception of the physical properties of an object. In the case of the Muller-Lyer illusion, the perception of different lengths for the two target lines occurs because the human visual system incorrectly calculates the probability distributions of the real-world sources of the lines based on the misleading context of the arrowheads. In summary, reduced top-down influences, with increased overreliance on bottom-up inputs might result in different susceptibility to VIs compared to healthy adults, which are also likely to vary between VIs. And although, it is not to suggest that visual perception of experts from Chapter V is immature, but this explanation would also suggest that those experts also show similar perceptual bias.

It was suggested in Chapter II (systematic review) that attentional deficits might contribute to children’s developing susceptibility to VIs. In addition to neurostructural maturation, age-related changes in VIs sensitivity may be attributed to the development of attentional mechanisms. The ability to sustain concentration across numerous trials is vital for the successful completion of many VI tasks. Barch et al. (2006) demonstrated that differences between schizophrenic adults (a population known to exhibit variations in VI susceptibility; see Costa et al., 2023 for a review) and neurotypical controls on a VI task became nonsignificant once differences in attention were accounted for. As children's capacity to maintain sustained attention evolves with age (Betts et al., 2006), it is conceivable that disparities in their VI susceptibility relative to adults could be elucidated by this factor. Hence, it could be hypothesized that children's performance is influenced, at least to some degree, by substituting their attention to detect size differences with a specific strategy aimed at minimising cognitive effort in the task (as discussed in more detail below). Such a strategy might lead to apparent differences in VI susceptibility compared to adults, thereby affecting various VI perceptions differently and explaining differences in susceptibility trajectories. Further research is needed to investigate this possibility.

Neurotypical children's attentional abilities undergo a protracted developmental trajectory, taking many years to reach an adult-like level (Konrad et al., 2005; McKay, Halperin, Schwartz, & Sharman, 1994). Indeed, research indicates that various aspects of visual attention develop at differing rates. For instance, Betts, McKay, Maruff, and Anderson (2007) observed rapid development in children's sustained attention between the ages of 5 and 9, while visual search abilities and the capacity to allocate attention to multiple objects concurrently continue to improve throughout adolescence (Dye & Bavalier, 2010). As such, attentional deficits may influence children's responses, with deficits referring to difficulties in maintaining focus and sustaining attention throughout a task (Hoonaker, Doignon-Camus, & Bonnefond, 2017). Consistent with the notion that children's sustained attention matures between the ages of 5 and 9 (Betts et al., 2007), many findings in VIs research, as highlighted in the systematic review, align with this timeline. For instance, around the age of 6-7 years, children begin to exhibit adult-like perception of certain VIs, such as the Ebbinghaus illusion (Doherty et al., 2010). Therefore, when examining the physical disparities of targets in VIs, attention plays a pivotal role. Despite the seemingly straightforward task of discerning the physical differences in VIs (e.g., the size of circles in the Ebbinghaus illusion), it remains demanding, particularly considering that the relative size differences between targets often start at a mere 2% variance (e.g., Doherty et al., 2010). Although not observed in Chapter III for the Ebbinghaus illusion, as the study comprised mostly well-performing children, this might explain other studies, such as Doherty et al. (2010). There the performance of children in the control condition was at chance, while here the children performed nearly at 100% accuracy. Future research should make direct comparisons between high- and low-performing children.

Here, it is important to further discuss the role of methodology in previous and current research. It was subtly suggested in Chapter IV that the method of adjustment might be the most suitable method of studying perceptual differences – it was done because of the larger PSE over 2AFC task. This implies that this method is more sensitive than 2AFC – however, it was only observed in a neurotypical sample of adults on the Muller-Lyer illusion. In order to provide more conclusive evidence for the greater reliability of this method further studies are needed, similar to those of Manning and colleagues (2017), where methodological differences were studied in three samples of autistic and neurotypical children. Such research will not only provide evidence for methods reliability, but most importantly it will provide more conclusive insight into the phenomena studied like perceptual organization in schizophrenia (Costa et al., 2024). Therefore, for the field of VI research to progress, the methodological differences ought to be studied in greater depth.

As demonstrated in Chapter IV, selecting only one particular method may reveal an effect that would not emerge using other approaches. Similarly, it may result in missing an effect that would be observed with alternative methods. For instance, if sex differences in Chapter II were examined solely using the 2AFC method, following Phillips et al. (2004), a significant reduction in susceptibility among males would be observed, leading the authors to conclude that males are less context sensitive. However, it was only through a more comprehensive approach, utilising a range of methods, that this effect was revealed to be method specific. This suggests that studies on susceptibility to VIs should employ a broader array of methodologies. Furthermore, as argued in Chapter II, it is likely that variations in stimuli contribute to the inconsistencies observed in previous research. Therefore, future researchers in this field should be cautious in interpreting their findings, as these may be constrained by the specific methods and stimuli used, rather than reflecting a true perceptual phenomenon.

Lastly, the examination of visual expertise in relation to VIs remains largely unexplored. Visual expertise encompasses a spectrum of abilities cultivated through intricate cognitive and perceptual processing, refined over extensive hours of practice and training (Sheridan & Reingold, 2017). According to Pascual-Leone and colleagues (2005), neuroplasticity refers to the nervous system's ability to adapt and refine its resources in response to physiological changes, injuries, evolving environmental demands, and sensory experiences (Pascual-Leone et al., 2005). In the realm of vision, previous studies have suggested that the brain possesses the capability to recover its visual functions (Baroncelli & Lunghi, 2021; Castaldi et al., 2020; Maino, 2009). For instance, restoring vision in adults who have experienced long-term blindness triggers reorganisation in the early visual cortex (Castaldi et al., 2020). These findings suggest that expertise in medical image interpretation may lead to alterations in the activation of various brain regions.

In line with this, Haller and Radue (2005) noted that radiologists exhibited heightened activation in specific brain regions, such as the bilateral middle and inferior temporal gyrus, and the left superior and inferior frontal gyrus, when viewing radiology images compared to control subjects. Additionally, non-radiology images elicited distinct activation patterns compared to controls. Radiologists showed the strongest activation in the left-dominant posterior superior and inferior parietal lobule, whereas controls demonstrated strongest activation in the right-dominant anterior superior and inferior parietal lobule and postcentral gyrus. These findings suggest that expertise in radiology results in unique patterns of brain activation, potentially leading to further structural changes in the brain. Reduced susceptibility to VIs, as observed in Chapter V, hints that potential changes at the structural level of the brain may occur, which then affect VI susceptibility. Further research should investigate where in the brain such changes occur, whether VI susceptibility can serve as a proxy for such changes, and if such changes occur in other domains of visual expertise such as chess.

Visual expertise may offer valuable insights into observed phenomena within the fields of radiology and radiography, as well as developmental changes in susceptibility to VIs. Variations in susceptibility among children under the age of five years could potentially be attributed to their limited exposure to the visual environment compared to adults, given that the child's brain undergoes continuous development throughout childhood (as discussed earlier; Sowell et al., 2004). For instance, the probabilistic strategy elucidated by Howe and Purves (2005) likely exhibits a developmental component. Children, owing to their comparatively lower overall cognitive capacity, may struggle to accurately compute these statistical relationships, thereby heightening susceptibility to certain VIs like the Muller-Lyer illusion. Moreover, the inability to accurately assess these relationships might also diminish susceptibility, as the developing visual system fails to accurately process contextual or pictorial depth cues. Nevertheless, these speculative hypotheses necessitate further empirical validation through rigorous testing, as many studies did not test children under five or even four years of age.

Radiologists and radiographers, through their visual expertise in medical image interpretation, may acquire visual skills that extend beyond their specialized domain. Our data indicate that the visual expertise gained in radiology may confer perceptual benefits that generalise to other visual tasks. It appears that individuals entering these professions are not inherently predisposed, based on pre-existing visual abilities, as expertise develops relatively early in their careers. In line with Howe and Purves' (2005) theory, these professionals may demonstrate greater accuracy in their responses compared to non-experts due to their finely tuned visual systems, which are adept at detecting subtle abnormalities, leading to more precise responses in VI tasks. Since perception relies on statistical relationship between stimulus elements and their potential physical origins, radiologists may have developed, through extensive training including looking at hundreds of medical images, a system that more accurately captures the 'objective' nature of ambiguous stimuli, like VIs. The aforementioned studies highlighting brain-related changes associated with expertise provide further support for this notion. Therefore, additional research is warranted to determine the timing of such changes and their correlation with structural alterations in the brain. This conclusion suggests that, in the absence of specialised visual expertise, susceptibility to the Ebbinghaus illusion is not dependent on extensive visual experience. Moreover, having more experience in perceiving the world does not lead to more accurate (or less accurate) perceptions of the Ebbinghaus illusion beyond the age of five. However, to warrant this assumption further it is necessary to further delve into lifespan research on the Ebbinghaus illusion.

The findings of Chapters III, V, and VI can be understood in terms of perceptual learning. As children develop, their visual attention shifts from a bottom-up, stimulus-driven approach to global processing (Acik et al., 2010; Donnelly et al. 2007). It can be suggested that a preference for attending to local, salient elements might therefore be advantageous during early development, as these might be easier to attend to by the still-developing visual system.

However, as more sense needs to be made out of the surroundings, the ability to visually integrate visual elements of the visual scenes becomes more profound. The findings of Chapter III suggest that this ability develops rather quickly – before the age of five (and that beyond a certain point further perceptual experience does not translate into further increase in susceptibility), and during the course of 'normal' life, the perceptual experience of females and males (Chapter IV) does not affect the ability to perceive VIs differently. However, as evident by the experiment in Chapter V, this ability can be learned – radiologists and reporting radiographers focus more on the local elements, ignoring the global context. It is also possible that the ability to bind global elements of the scene is somewhat reduced with aging and the physiopathology of certain brain areas as seen in Chapter VI – which could be seen as opposite of learning but rather perceptual forgetting. These findings collectively support the idea that visual perception, namely context integration and pictorial depth perception, is a dynamic process that undergoes changes across the lifespan due to expertise development or acquisition of neurodegenerative disorders.

The experiment in Chapter V showed that perceptual learning may affect the perception of novel stimuli outside of the practice zone. Despite its novelty, this finding is perhaps unsurprising. Practice across a multitude of areas shows the transfer of learning, beyond what is actually practiced upon, which can be considered as by-products of such practice. For example, physical exercise has been repeatedly shown to have a positive impact on well-being and cognitive functioning (for a review see Mandolesi et al., 2018). Other areas include improved visual attention among gamers compared to non-gamers (Matern et al., 2019) or enhancements of cognitive ability as a result of bilingualism (for a review, see Fox et al., 2019). While it might be unsurprising that expertise in radiology results in perceptual by-products, it is surprising that such a by-product is not related to visual search abilities, nor wider top-down influences (as observed in other studies on radiology expertise – see Sheridan and Reingold, 2017, for an overview), but strict bottom-up, local perception. Future studies, from across visual expertise domains, like chess (research shows that chess experts, just like radiologists, have superior abilities in chess-related tasks that require visual processing – for a review see Reingold & Sheridan, 2012) should investigate whether the visual expertise results in perceptual changes at a local level.

Implications and Suggestions for Further Research

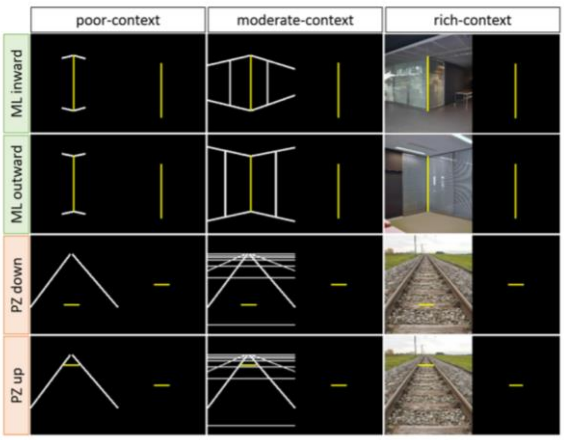
The implications and avenues for future research are plentiful. Firstly, it is imperative to revisit the developmental trends regarding susceptibility to VIs. As demonstrated in Chapter III, our findings indicate that children exhibit comparable susceptibility to the Ebbinghaus illusion as adults across various methodologies. This contradicts several previous studies in the field, such as those by Doherty et al. (2010) and Kaldy and Kovacs (2003). This was attributed to the greater cognitive ability of the tested sample. As compared with the previous study by Wincza and colleagues (in preparation) who also used a 2AFC paradigm after Philips et al. (2004), the number of children excluded due to failing the control condition was much smaller. In line with their data, that reduced susceptibility to the Ebbinghaus illusion is negatively correlated with non-verbal intelligence scores, it suggests that children who do not attend carefully to the task tend to have higher scores compared to children who do so. This provides compelling evidence that if instructions are followed, children do not exhibit reduced susceptibility to the Ebbinghaus illusion. This evidence suggests that prior research might not have adequately assessed the ability to perceive subtle changes in size, instead possibly capturing aspects of children's strategic approaches. Hence, future investigations should explore whether previously observed developmental trends in VIs are influenced by children's strategic utilisation. One potential avenue for inquiry is the analysis of children's eye movements, which could shed light on their fixation patterns and scanning strategies. If children employ specific strategies, these may manifest as rapid fixations toward preferred areas while largely disregarding other stimuli. Future research should also investigate whether children with lower cognitive abilities, as measured by assessments like Raven's matrices for non-verbal intelligence, may be less inclined to rely on strategic approaches compared to their cognitively more proficient counterparts – as indicated by different eye movements and increased susceptibility to VIs. If validated, susceptibility to VIs could serve as a potential predictor of children's cognitive abilities.

This research has focused solely on methodological disparities in children using the Ebbinghaus illusion. This narrow scope limits the generalisability of our findings to other VIs thus necessitating further research incorporating additional illusions such as the Ponzo or Muller-Lyer, as this will provide further insight into the development of perceptual abilities of children. In line with the conclusions drawn in Chapter II, it is imperative to explore susceptibility to VIs not only across various methodologies but also across different iterations of the same VIs. This approach would facilitate a deeper understanding of whether observed developmental trajectories are specific to individual illusions (e.g., effects related to size contrast) or within-illusion specific (e.g., differing versions of the same illusion yielding distinct developmental trajectories). Such investigations would not only contribute to elucidating the developmental aspects of various VIs but also unravel the intricacies of each specific VI under study. Most importantly, it would help establishing whether young children in fact do not integrate context visually to the same extent as adults.

Another notable aspect emphasized by the research conducted in this thesis warrants further investigation: the potentially diminished ability of Parkinsonian patients to integrate depth cues. While it was found that susceptibility to the Ponzo illusion is reduced in PD, the finding was marginally significant. It is noteworthy that online studies tend to replicate findings from in-person, lab-based studies, albeit with effect sizes typically twice as large (e.g., a developmental meta-analysis by Chuey et al., 2022). This suggests that the observed effect may be more robust than initially observed and thus merits more in-depth exploration. Future studies should consider manipulating the presence of depth cues, ranging from absent to rich levels (see Figure 1 below). If Parkinsonian patients struggle to perceive pictorial depth, a greater discrepancy between them and neurotypical adults should be evident with stronger depth cues, as previous studies show that adding depth cues enhances the magnitude of some VIs like the Shepard Table Tops illusion (Songhorabadi et al., 2022). Subsequent research should aim to test this hypothesis. If supported, this line of inquiry holds potential implications for developing coping strategies and interventions, such as informing PD patients about their potential depth deficits and supporting them in compensating for those deficits, aimed at mitigating the risk of falling, as previous research has linked reduced depth perception to an increased risk of falls (Cummings et al., 1995). Furthermore, these findings show that the ability to integrate context visually remains intact in PD, as the susceptibility to the Ebbinghaus and Ponzo illusions did not differ in individuals with PD and without. It then goes on to suggest that the pathophysiology of the basal ganglia and dopamine reductions do not impact on context integration.

Figure 1

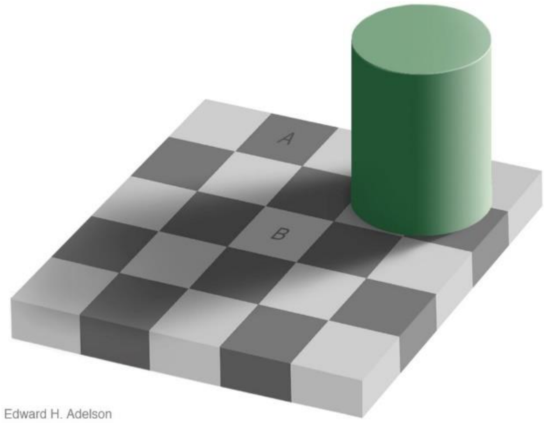
Manipulation of Different Levels of Depth by Cretenoud et al. (2020)



In conclusion, further research into the perception of pictorial depth, context integration, and size constancy mechanisms within the field of radiology and radiography is warranted. Building upon the suggestions outlined above regarding the potential impact of reduced pictorial depth perception in the Ponzo illusion on the differentiation between healthy controls and Parkinsonian patients, we posit that similar trends may be observable among radiologists and radiographers. Because radiologists and radiographers frequently turn 2-D images into 3-D representations of the human body they might be better equipped to counterbalance the illusory effects in pictures. Future investigations should explore this hypothesis. Moreover, many previous studies examining the visual abilities of radiologists and radiographers have primarily focused on their performance within the familiar context of medical images. Therefore, integrating VIs into medical images could offer valuable insights into how context is integrated by these professionals. For example, including similarly sized nodules surrounded by either larger or smaller than the nodule context that resembles human tissue to imitate the Ebbinghhaus illusion. Additionally, this line of inquiry should extend to VIs involving colour perception, such as Adelson's Checker Shadow illusion (Perceptual Science Group, see Figure 2 below). This expansion would provide a further understanding of the distinctions between low-level and high-level VIs (King et al., 2017). It is plausible that radiologists and radiographers, who are accustomed to visually enhancing contrast, may exhibit heightened susceptibility to VIs relying on variations in shade compared to individuals lacking expertise in radiology.

Figure 2

Adelson's Checker Shadow Illusion



Note. Squares A and B are of identical shade of grey.

Limitations of the Thesis

The thesis acknowledges certain limitations in its approach to summarising research on children's susceptibility to VIs. Initially, the systematic review focused solely on a subset of VIs, omitting others such as the Solitaire illusion (Parrish et al., 2016) or the Jastrow illusion (Murray, 1965). It was assumed that attention should be directed toward the most extensively researched VIs. However, it is now recognised that including a general section summarising these VIs would offer valuable insights into children's susceptibility to VIs and shed more light on discussed methodological differences. Future studies should investigate these VIs from a developmental perspective. Moreover, it is now acknowledged that the initial focus solely on a systematic review, without supplementing it with a meta-analysis, was inadequate. It became apparent during the write-up that conducting a meta-analytic approach would serve little purpose due to many reported studies lacking key details, like means and standard deviations, necessary for such analysis. This is unsurprising given the dated nature of many studies in the field, with writing standards evolving over decades. Nevertheless, even if only a small proportion of these studies were included, the data would still provide insights into developmental trends of VIs, particularly for those like Ebbinghaus or Ponzo, where evidence is mixed. In the future, researchers are urged to consider conducting such an analysis to strengthen the points made in the systematic review and to encompass other VIs omitted from this review. This comprehensive approach will offer a more compelling and holistic understanding of the development of VIs susceptibility and the underlying processes behind their effects.

The pandemic and post-pandemic reality has significantly impacted the conducted research. For example, as many of the experiments have been conducted remotely (or partially remotely), visual angles were not possible to be calculated. It suggests that some participants might have had different viewing conditions and perceived the VIs differently to others because of that. However, the VIs studied here have strong and robust perceptual effects (i.e., research does not suggest that the VIs studied here are contingent upon very specific viewing conditions), therefore, it is unlikely that these small differences could affect overall susceptibility scores for the participants. Furthermore, the developmental research intended for this thesis was also severely affected. Securing child participants post-COVID-19, particularly from schools, proved challenging, greatly hampering data collection efforts. To adapt to logistical difficulties of recruitment, Chapter III's experiment focused solely on the Ebbinghaus illusion. Future studies should extend this research to include other visual illusions, such as Ponzo or Vertical-Horizontal illusions, to yield more robust evidence regarding methodological differences in children's perception. As these VIs also seem to be affected by methodological differences and are mediated by different perceptual mechanisms, children might likely respond to these VIs differently. Future investigations should also explore susceptibility variations between high- and low-scoring children in the control condition. Since Chapter II's experiment primarily involved mainly high-scoring participants (meaning that the children attended to the task successfully) and lacked data on their non-verbal intelligence, the assertions made there remain speculative. It is imperative for subsequent research to delve deeper into these differences. As emphasized in Chapter II's systematic review, forthcoming studies should also examine variations in stimuli. Would children's susceptibility differ depending on the specific version of an illusion employed? It seems that some previous findings may be specific to certain methods or types of illusions. This insight would help to further understand whether illusion types of differing magnitudes are equally affected by development and whether the developing, perceptual system is sensitive to these changes. Therefore, this avenue of research warrants further exploration to address potential technical confounds highlighted in the systematic review.

Chapter IV also has its limitations. Following data collection, it was discovered that a technical error prevented analysis of Ponzo illusion data using the 2AFC method without randomisation. Alongside the data for the Ebbinghaus and Müller-Lyer illusions, this dataset could have provided much more compelling evidence of sex differences in susceptibility to VIs, particularly considering previously reported sex differences on that illusion (e.g., Miller, 2001). Expanding beyond the Ponzo illusion, future research should investigate methodological differences in adults using other visual illusions, such as the Poggendorff or Vertical-Horizontal illusions. Furthermore, many of the limitations observed in the developmental field (including methodological and stimulus variations) should be explored among adults. If the study of visual illusions is to be helpful and useful in uncovering the workings of the human visual system, the methods and stimuli used should undergo validation beyond current knowledge.

Chapters II, III, and IV have predominantly focused on methodological differences and potential confounds associated with different methods. However, the study examining VIs susceptibility among radiologists exclusively employed the 2AFC method (following Phillips et al., 2004), suggesting that these findings may be method-specific rather than indicative of the general abilities of radiologists and radiographers. Perhaps radiologists and radiographers have differing thresholds in situations of uncertainty (when the target and comparison object are very similar), however, their perceptual 'true match' might not differ largely from non-experts. Alternatively, in situations of uncertainty experts might be more influenced by their reasoning about the illusion that non-experts. Future studies should investigate this hypothesis. Two primary reasons underlie the decision to utilise only one method. Firstly, the initial data collection occurred five years ago, when such concerns were not prominent in the literature. Secondly, due to the challenges of recruiting radiologists and radiographers and the limited time available to them, it was determined to utilise the method previously employed, namely the 2AFC method following Phillips et al. (2004). This choice paves the way for future studies to replicate the current findings using different methods, such as MOA or 2AFC without randomisation. If subsequent research replicates the earlier results, it will offer compelling evidence for the role of visual expertise in medical image interpretation on VI susceptibility. Conversely, it will further highlight methodological disparities in the field, necessitating additional empirical investigations to uncover the underlying psychological processes associated with these methods.

Two additional limitations are evident in Chapter VI. Firstly, similar to Chapter V, the susceptibility to VIs in PD patients was assessed solely using the MOA. The primary reason for this decision was that, after administering the first two participants, the total study duration approached 90 minutes, which was deemed too lengthy for the participants. Consequently, the decision was made to forego the 2AFC without randomisation. Therefore, in the study of PD patients, future research should investigate whether their susceptibility is influenced by the method used, thereby further validating the findings obtained in Chapter VI. Despite ensuring optimal viewing conditions for online testing, it is acknowledged that the effect sizes for online research tend to be approximately half the size of those observed in in-person research (Chuey et al., 2022). This suggests that the effect observed for the Ponzo illusion might be stronger than previously believed. Hence, future studies should explore this possibility. Finally, more direct research is required to compare online testing with traditional lab-based experiments. To streamline future research on VIs, subsequent studies should investigate how data obtained online, using platforms like Prolific, differ from traditional lab-based experiments. Transitioning to online testing would facilitate the recruitment of hard-to-reach populations, such as radiologists, the elderly, or even children.

Lastly, as many of the experiments have been conducted remotely, visual angles were not possible to calculated, thus suggesting that some participants might have had different viewing conditions and perceived the VIs differently to others. However, the VIs studied here have strong and robust perceptual effects. Therefore, it is unlikely that these small differences could affect overall susceptibility scores for the participants.

Conclusion

Throughout this PhD thesis, it has been demonstrated that context integration and pictorial depth perception are complex components of visual perception influenced, at least partially, by factors such as sex, visual expertise, and structural changes in the brain. Additionally, the research has shed light on potential limitation in drawing conclusions from studies employing VIs paradigms – the selection of methodology used results in different illusions magnitude at least for the Muller-Lyer illusion, as well as different methods can produce differing susceptibility scores between sexes for the Ebbinghaus illusion. These findings challenge many previously established beliefs in the field, necessitating a reassessment of claims regarding context integration and pictorial depth perception. The data and conclusions presented in this thesis have the potential to significantly contribute to theoretical frameworks concerning how context integration and pictorial depth are processed in the brain. It was shown that these develop before the age of five, contrary to previous accounts (e.g., Doherty et al., 2010), as well as the findings obtained are contingent on the methodology used. Furthermore, it was shown that expertise in medical image interpretation affects VIs susceptibility, providing new insights into processes underpinning VI susceptibility. It suggests that the ability to ignore irrelevant context reduces VIs, implying that stronger bottom-up influences reduce VIs susceptibility. Finally, the findings suggest that pathophysiology of the basal ganglia and reduced dopamine are not linked to context integration but may potentially be linked to pictorial depth perception (although further evidence is required to support this claim). Moreover, they are likely to stimulate further investigations into how depth perception is impacted by Parkinson's disease (PD), as well as the changes in context integration and size constancy mechanisms resulting from extensive training in medical image interpretation. These insights hold promise for practical implications, such as developing specific training targeting perceptual abilities, which could lead to the reduction of errors in medical image interpretation and mitigating the risk of falls among the elderly.

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Appendices

Chapter V

Supplementary Materials – Model Building Sequences

General Information.

Non-experts were coded as -0.5 while experts were coded as 0.5. Stimuli size difference (%) between comparison stimuli was coded as 2, 6, 10, 14, and 18 for the Ebbinghaus and Shepard Tabletops illusions, and 4, 12, 20, 28, and 36 for the Muller-Lyer and Ponzo illusions. The dependent variable was response accuracy – for each trial per VI the participant could score 0 (incorrect answer) or 1 (correct answer). The likelihood of responding correctly was 50%. Data were analysed via generalised linear mixed effects models in R (R Core Team, 2019) using the glmer function from the lme4 package (Bates et al., 2015).

Ebbinghaus Illusion.

The baseline model (Model 1) contained a by-participant random intercept with a random slope of stimuli size difference (z = -18.36, p < .001). Then, the fixed effect of the group was added (Model 2), significantly improving the fit compared to the baseline model (Model 1: χ^2 = 11.92, p < .001). We then added the stimuli size difference (Model 3) which improved the model fit over the baseline model (Model 1: χ^2 = 183.16, p < .001). Furthermore, we included both effects combined (Model 4), which also improved the model fit over the previous two models (Models 2 and 3; χ^2 = 188.35, p < .001; χ^2 = 17.11, p < .001, respectively). Finally, adding an interaction effect between stimuli size difference and group (Model 5) did not significantly improve the model (Model 4: χ^2 = 1.01, p < .315).

While testing individual differences, adding age (Model 6) did not significantly improve the best-fitting model (Model 3; χ^2 = 1.72, p = .190), while adding sex as a factor (Model 7) marginally improved it (Model 7: χ^2 = 4.27, p = .039). Both years of experience

(Model 8) and images per day (Model 9) failed to improve the base-fitting model (Model 3; $\chi^2 < 0.01$, $p = .948$; $\chi^2 < 0.01$, $p = .978$).

Ponzo Illusion.

The baseline model (Model 1) contained a by-participant random intercept with a random slope of stimuli size difference ($z = -11.13$, $p < .001$). Then, the fixed effect of the group was added (Model 2), significantly improving the fit compared to the baseline model (Model 1: $\chi^2 = 4.69$, $p = .030$). We then added the stimuli size difference (Model 3) which improved the model fit over the baseline model (Model 1: $\chi^2 = 282.34$, $p < .001$). Furthermore, we included both effects combined (Model 4), which also improved the model fit over the previous two models (Model 2 and 3: $\chi^2 = 283.88$, $p < .001$; $\chi^2 = 6.23$, $p = .013$, respectively). Finally, adding an interaction effect between stimuli size difference and group (Model 5) did not significantly improve the model (Model 4: $\chi^2 = 2.35$, $p < .125$).

While testing individual differences, adding age (Model 6) did not significantly improve the best-fitting model (Model 4: $\chi^2 =1.21$, $p = .272$), while adding sex as a factor (Model 7) also improved the model (Model 4: $\chi^2 = 5.56$, $p = .018$). Both years of experience and images per day (Models 8 and 9) failed to improve the best-fitting model (Model 4: $\chi^2 = 0.01$, $p = .815$; $\chi^2 = 1.84$, $p = .178$).

Muller-Lyer Illusion.

The baseline model (Model 1) contained a by-participant random intercept with a random slope of stimuli size difference ($z = -18.36$, $p < .001$). Then, the fixed effect of the group (Model 2) was added, significantly improving the fit compared to the baseline model (Model 1: $\chi^2 = 15.44$, $p < .001$). We then added the stimuli size difference (Model 3) which improved the model fit over the baseline model (Model 1: $\chi^2 = 282.45$, $p < .001$). Furthermore, we included both effects combined (Model 4), which also improved the model fit over the previous two models (Models 2 and 3; $\chi^2 = 279.36$, $p < .001$; $\chi^2 = 12.35$, $p < .001$, respectively).

Finally, adding an interaction effect between stimuli size difference and group (Model 5) significantly improved the model (Model 4: χ^2 = 9.93, p = .002). The interaction is deconstructed in the main text.

While testing individual differences, adding age (Model 6) did not significantly improve the best-fitting model (χ^2 = 0.14, p = .713), while adding sex as a factor (Model 7) also improved the model (χ^2 = 0.47, p = .495). Both years of experience and images per day failed to improve the best-fitting model (Models 8 and 9: χ^2 = 0.62, p = .431; χ^2 = 1.95, p = .163).

Shepard Tabletops Illusion.

The baseline model (Model 1) contained a by-participant random intercept with a random slope of stimuli size difference (z = -18.36, p < .001). Then, the fixed effect of the group was added (Model 2), which did not significantly improve the fit compared to the baseline model (Model 2: χ^2 = 1.08, p = .300). We then added the stimuli size difference (Model 3) which improved the model fit over the baseline model (Model 1: χ^2 = 234.98, p < .001). Including both factors together (Model 4) improved the model fit over the group-only model (Model 2: χ^2 = 235.14, p < .001) but not the stimuli size difference-only model (Model 3: χ^2 = 1.24, p = .265). Finally, adding an interaction effect between stimuli size difference and group (Model 5) did not significantly improve the model (Model 3: χ^2 = 3.37, p < .186).

While testing individual differences, adding age (Model 6) did not significantly improve the best-fitting model (Model 3: χ^2 =1.53, p = .465), while adding sex as a factor (Model 7) also did not improve the model (Model 3: χ^2 =2.55, p = .279). Years of experience (Model 8) failed to improve the model (Model: χ^2 = 0.61, p = .433) and images per day (Model 9) improved the best-fitting model (Model 3: χ^2 = 4.82, p = .028).

Pairwise Comparisons

For experts, the Ebbinghaus illusion's scores (M = 9.16, SD = 5.16) significantly differed from Ponzo's (M = 12.05, SD = 3.00; t(44) = -4.40, p < .001, d = -0.64, BF10 = 193.60) and Shepard's (*M* = 6.86, *SD* = 3.15; *t*(44) = 3.50, *p* = .006, *d* = 0.42, BF10 = 4.81), but not the Müller-Lyer's (*M* = 9.55, *SD* = 1.78; *t*(44) = -0.59; *p* = 1, *d* = - 0.07, BF10 = 0.18). Furthermore, Ponzo's scores (*M* = 12.05, *SD* = 3.00) differed significantly from Müller-Lyer's scores (*M* = 9.55, *SD* = 1.78; *t*(44) = 3.81; *p* = .002, *d* = 0.66, BF10 = 283.45) and Shepard's scores (*M* = 6.86, *SD* = 3.15; *t*(44) = 7.90, *p* < .001, *d* = 1.43, BF10 = $1.914 \text{x} 10^{+9}$). Finally, scores for the Müller-Lyer's scores (*M* = 9.55, *SD* = 1.78) differed significantly from Shepard's (*M* = 6.86, *SD* = 3.15; *t*(44) = 4.09, *p* < .001, *d* = 0.74, BF10 = 1541.84). For the non-experts, the Ebbinghaus illusion's scores (*M* = 5.75, *SD* = 4.61) significantly differed from Ponzo's (*M* = 10.51, *SD* = 3.36; *t*(107) = -11.38, *p* < .001, *d* = -0.97, BF10 = $1.223 \text{x} 10^{+14}$) and Müller-Lyer's (*M* = 8.49, *SD* = 1.76; *t*(107) = -0.51, *p* < .001, *d* = -0.55, BF10 = 109617.46), but not the Shepard's (*M* = 5.99, *SD* = 2.69; *t*(44) = -0.58; *p* = 1, *d* = - 0.05, BF10 = 0.12). Furthermore, Ponzo's scores (*M* = 10.51, *SD* = 3.36) differed significantly from Müller-Lyer's scores (*M* = 8.49, *SD* = 1.76; *t*(44) = 4.80; *p* < .001, *d* = 0.53, BF10 = 52167.46) and Shepard's scores (*M* = 5.99, *SD* = 2.69; *t*(44) = 10.74, *p* < .001, *d* = 1.21, BF10 = $3.304 \text{x} 10^{+19}$). Finally, scores for the Müller-Lyer's scores (*M* = 8.49, *SD* = 1.76) differed significantly from Shepard's (*M* = 5.99, *SD* = 2.69; *t*(44) = 5.94, *p* < .001, *d* = 0.76, BF10 = $2.105 \text{x} 10^{+9}$).