A critical review of the cognitive and perceptual factors influencing attentional

scaling and visual processing

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Abstract

An important mechanism used to selectively process relevant information in the environment is spatial attention. One fundamental way in which spatial attention is deployed is attentional scaling: the process of focusing attentional resources either narrowly or broadly across the visual field. Although early empirical work suggested that narrowing attention improves all aspects of visual processing, recent studies have demonstrated that narrowing attention can also have no effect or even a detrimental impact when it comes to vision that is thought to be mediated via the magnocellular pathway of the visual system. Here, for the first time, we synthesise empirical evidence measuring the behavioural effects of attentional scaling on tasks gauging the contribution of the major neural pathways of the visual system, with the purpose of determining the potential factors driving these contradictory empirical findings. This analysis revealed that attentional scaling could be best understood by considering the unique methodologies used in the research literature to date. The implications of this analysis for theoretical frameworks of attentional scaling are discussed, and methodological improvements for future research are proposed.

A critical review of the cognitive and perceptual factors influencing attentional scaling and visual processing

Introduction

On a moment to moment basis, our brains are inundated with vast streams of visual information. Spatial attention is one way that the brain selects key pieces of information for enhanced processing. Numerous studies over the past four decades have demonstrated that spatial attention is highly dynamic. Firstly, attention can be *shifted* across the visual field (Carrasco, 2011; Posner, 1980; Posner & Cohen, 1984). Second, it can be *split* into discontinuous locations in space (Castiello & Umiltà, 1992; Muller, Malinowski, Gruber, & Hillyard, 2003; however, see Jans, Peters, & De Weerd, 2010). Finally, attention can be *scaled* to varying sizes (Eriksen & James, 1986; Eriksen & Yeh, 1985; Greenwood & Parasuraman, 1999, 2004; Müller, Bartelt, Donner, Villringer, & Brandt, 2003). When attention is focused on a constrained area of visual space, it is said that an individual has adopted a *narrow attention scale*. When spatial attention is spread over a relatively diffuse region, the individual has adopted a *broad attention scale* (Figure 1). Here, we are interested in this third facet of spatial attention: *attention scaling*.

Figure 1. Examples of attentional scaling. While attentional shifting involves the movement of spatial attention resources across the visual field to varying locations of interest, attentional scaling involves both the narrowing and broadening of attentional resources according to task demands. The left figure shows a broad scale of attention, while the right figure shows a narrow scale of attention.

Elucidating the relationship between scaling and vision has far-reaching implications in a number of clinical and research domains. Attentional scaling is known to influence performance in everyday activities such as reading, driving, and visual search (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Ball & Sekuler, 1986; Facoetti et al., 2003; Greenwood & Parasuraman, 1999). Furthermore, there are demonstrated deficits in attentional scaling for conditions including dyslexia, schizophrenia, and Alzheimer's disease (Elahipanah, Christensen, & Reingold, 2011; Facoetti & Molteni, 2001; Greenwood, Parasuraman, & Alexander, 1997; Vidyasagar, 1999). Finally, recent work has demonstrated that training programs may be effective at improving the flexibility of attentional scaling processes (Fang et al., 2017; Rolle, Anguera, Skinner, Voytek, & Gazzaley, 2017). This highlights the potential for improving everyday functioning for individuals with attentional-perceptual deficits. Taken together, this is why understanding the effect of attentional scaling on visual perception has become the focus of a recent line of research.

To the best of our knowledge, currently, no literature reviews exploring attentional scaling and visual perception exist. This is problematic, as a survey of the literature exploring attention scaling and vision could understandably leave one confused, with studies often arriving at contradictory conclusions. Although an early theory of attentional scaling assumed that narrowing attention unequivocally improved visual processing, recent work has shown this is not necessarily the case, wherein some instances, narrow attention has had either no impact, or even impaired visual processing (Chong & Treisman, 2005; Goodhew, Lawrence, & Edwards, 2017; Goodhew, Shen, & Edwards, 2016; Mounts & Edwards, 2017; Shulman & Wilson, 1987). To address these inconsistencies, three more recent accounts of attentional scaling and vision have been proposed: the selective spatial enhancement (SSE) account (Burnett, d'Avossa, & Sapir, 2013; Goodhew et al., 2017, 2016) the spatiotemporal trade-off account (STA; Goodhew et al., 2016; Shulman & Wilson, 1987), and the attentional

attraction field (AAF) account as applied to attentional scaling (Baruch & Yeshurun, 2013; Mounts & Edwards, 2017). However, empirical evidence supporting each theory is not only limited but conflicting. This is particularly true for studies measuring the effect of scaling on processes thought to be mediated by the magnocellular channel of the visual system, such as temporal resolution and low-spatial-frequency perception (Goodhew et al., 2017, 2016; Goto, Toriu, & Tanahashi, 2001; Mounts & Edwards, 2017; Poggel, Treutwein, Calmanti, & Strasburger, 2006).

Therefore, the purpose of this review is to synthesise the evidence from studies exploring scaling and visual perception in order to determine potential reasons for inconsistencies across the literature and to, therefore, guide future research. Firstly, we summarise the major theoretical accounts of attentional scaling and vision, and present key evidence favouring each theory. Following this, we examine how these key pieces of experimental evidence supporting each theory differ in their methodology. Factors covered in this analysis include the roles of endogenous versus exogenous attention, the use of stimuli which may cause an annular distribution of attention rather than attention scaling, the complex influences of perceptual and cognitive load, as well as the influence of varying stimulus eccentricity to manipulate and measure magnocellular mediated visual processing. Although this is not an exhaustive list of factors which influence the relationship between attention scaling and vision, by evaluating how each methodology used may lead to particular effects of spatial attention on vision, we hope to clarify the scope of each attentional scaling theory.

Theoretical Accounts of Attention Scaling and Vision

Zoom lens account

The zoom lens account is by far the most pervasive account of attentional scaling and vision in the literature (Eriksen & James, 1986; Eriksen & Yeh, 1985). This account proposes

that the primary function of attentional scaling is to enhance visual processing based upon task demands. While broad attention allows for the processing of more global information over a large region of visual space, narrowing attention allows one to concentrate their cognitive resources for enhanced resolution, i.e., visual acuity, within a smaller region. In other words, the zoom lens account espouses a trade-off between a broad scale for improved global processing versus a narrow scale for enhanced visual resolution. Thus, this account assumes that narrow attention unequivocally improves visual resolution relative to broad attention.

Indeed, early research demonstrated that this was the case for commonly used perceptual tasks such as target detection, whereby narrow attention improved response times compared to broad attention (Barriopedro & Botella, 1998; Eriksen & James, 1986; Eriksen & Yeh, 1985; Greenwood & Parasuraman, 1999). For example, Eriksen and James (1986) measured the influence of attentional scaling for letter target processing. Specifically, the participants' attentional scale was set using a cueing procedure, where the number of cued areas was manipulated to alter the spatial scale of attention. It was assumed that when the cued number of letters was small, attention was narrowed and that with increasing letter positions cued, attention was broadened. In line with the zoom lens account, response times were faster under narrow, compared to broad attention. This suggests that a narrow scale of attention improves visual resolution.

Following the initial study of the zoom lens account, a series of studies conducted by Umiltà and colleagues attempted to determine the extent over which attentional resources could be deployed using a modified Posner cueing procedure (Benso, Turatto, Mascetti, & Umiltà, 1998; Castiello & Umiltà, 1990; Posner, 1980; Turatto et al., 2000; Umiltà, 1998). For example, to measure the effects of attention scaling on visual perception, while ruling out the role of attentional shifting, Turatto and colleagues (2000) measured how response times

for target detection changed following the appearance of either small (2.5 °radius) or large

(7.5 °radius) circular pre-cues which indicated the location of a target to be detected. Similar

to past work, it was found that target detection speeds were faster for smaller attentional cues

compared to larger attentional cues.

Nonetheless, it is critical to emphasise that these early studies of attentional scaling

and visual perception inferred visual processing capacity by comparing *response times*

(Castiello & Umiltà 1990; Eriksen & Yeh, 1985; Turatto et al., 2000). In contrast, relatively

less work has explored the influence of broad and narrow attention on *visual perception*,

using accuracy (or sensitivity) measures, for tasks targeting specific areas of the visual

system. The distinction between response time and accuracy is crucial, as it is possible that

response time measures do not reflect the same visual cognitive processes as do accuracy

measures. Indeed, accuracy and sensitivity measures are thought to reflect early perceptual

processes, whereas response time measures might reflect both perceptual processes, as well

as response selection and motor processes (e.g., Bashinski & Bacharach, 1980; Prinzmetal,

McCool & Park, 2005; Santee & Egeth, 1982). As such, studies which use accuracy tasks to

measure performance will be the focus of the remainder of the review paper.

In contrast to studies measuring response time differences, there have been a small

series of studies that have shown attention scaling influences visual processing performance

using both accuracy, sensitivity, and neuroimaging measures. For example, the influence of

scaling on spatial acuity has been studied using a Vernier acuity task (Balz & Hock, 1997). In

Experiment 1 of this study, participants were shown 19 dots presented along the horizontal

meridian (0.5 °x 0.5 °in size, spanning 9.8 °of visual angle). Attention scale was varied by

asking participants to detect changes in the brightness of the different dots. The change could

occur in the dot presented at fixation (small scale of attention), or in any one of 9 dots

(centred around the central dot - large attention). The participants also decided whether a line

presented below the luminance dots was aligned. Overall, it was found that a small spatial scope of attention improved visual resolution at the attended region for this task.

Likewise, Poggel et al. (2006) found narrow attention improved temporal resolution (detecting fast changes in luminance across time). Here, a visual search task was used to manipulate attention scale. Double pulse temporal resolution at different spatial scales was then measured. On each trial, eight white light stimuli were presented concentrically around a white light shown in the middle of the display. Eight of the lights were shown continuously for the entire display duration, and one of the lights flickered. Following each presentation, participants indicated the location of the double pulse, so it was assumed that all nine positions were simultaneously monitored. Critically, the spatial layout of the lights was varied between each block, where within a block, the circle of lights was either narrowed into smaller eccentricities (i.e., narrow attention) or widened to cover larger areas of the visual field (i.e., broad attention). The range of stimulus eccentricities was from 2.5° through to 20° from fixation. A threshold for temporal resolution was calculated so that for each condition, the minimum temporal gap in the double pulse presentation was determined. Overall, it was found that for the centrally presented light, thresholds to detect the double pulse decreased, suggesting that temporal resolution increased under narrow attention. Thus Poggel et al. (2006) demonstrated that narrowing of attention can improve temporal resolution, providing further support for the zoom lens account

Finally, there is neuroimaging evidence which shows that attention scaling can influence visual processing mediated by the visual cortex (Müller et al., 2003; Sasaki et al., 2001). For example, Müller et al. (2003) found that under narrow attention, activation in the primary visual cortex was modulated, such that there was increased magnitude of activation over a smaller region of the visual cortex for narrow attention, relative to broad attention. For

broad attention, a larger region of the visual cortex was activated, but to a lesser extent. This is broadly consistent with the zoom lens account.

Selective spatial enhancement account

Although early research suggests that narrowing attentional scale enhances all aspects of visual resolution (e.g., Balz & Hock, 1997; Müller et al.. 2003; Poggel et al, 2006), a contrasting literature had found that not all types of visual resolution are enhanced (Chong & Treisman, 2005; Goodhew et al., 2017, 2016; Mounts & Edwards, 2017; Pringle, Irwin, Kramer, & Atchley, 2001; Yeshurun & Carrasco, 2008). To explain these contrasting effects, Goodhew et al. (2017, 2016) suggested that attentional scaling effects on visual perception may be largely reliant on the extent to which the stimulus is processed by the magnocellular or the parvocellular visual pathway (Goodhew et al., 2017, 2016).

Decades of physiological and behavioural data have demonstrated that the human brain processes visual information via parallel pathways, and that the cells in these pathways are specialised for processing different types of visual information (Derrington & Lennie, 1984; Livingstone & Hubel, 1988; Nassi & Callaway, 2009; Nassi, Lyon, & Callaway, 2006; Schiller, Logothetis, & Charles, 1990). Two of the predominant visual channels are the parvocellular and magnocellular channels (named after cells in the lateral geniculate nucleus). Table 1 summarises their key properties. Although there is not a complete demarcation, at the limits of perceptual processing, parvocellular and magnocellular neurons differ in the visual information they are most sensitive to. Parvocellular neurons are better able to process rapid changes in luminance across space (high spatial frequencies corresponding to fine spatial details in a scene), and less able to process rapid changes across time. In contrast, magnocellular neurons are better able to process gradual luminance changes across space (low spatial frequencies corresponding to coarse spatial details of a scene), and fast luminance changes over time, having higher temporal resolution (Butler & Javitt, 2005;

Butler et al., 2006; Denison, Vu, Yacoub, Feinberg, & Silver, 2014; Derrington & Lennie,

1984; Goodhew et al., 2017; Livingstone & Hubel, 1988; Öğmen, Purushothaman, &

Breitmeyer, 2008; Schulte-Körne, Remschmidt, Scheuerpflug, & Warnke, 2004).

To infer changes in the relative contribution of the parvocellular and magnocellular

systems of perception, a large host of behavioural studies have used tasks specifically

designed to tap into visual processing mediated by the two pathways. For instance, in acuity

tasks, participants are required to detect small spatial gaps in stimuli, or temporal

discontinuities in brief stimulus presentations (Figure 2). The spatial-gap task requires fine

spatial resolution and hence taps the parvocellular system, while the temporal-gap task

requires fine temporal resolution and hence taps the magnocellular system. Likewise, changes

in the perception of high and low-spatial-frequency stimuli are measured by comparing

performance on orientation discrimination tasks (Figure 3). Although some authors have

suggested that parvocellular and magnocellular activation cannot be reliably measured using

behavioural methods (e.g. Skottun, 2013; Skottun & Skoyles, 2011), a large host of empirical

studies exploring both attention, motor processing and clinical deficits refute this (see

Goodhew et al., 2017 for a brief review of this issue).

The relative input of parvocellular and magnocellular neurons to visual processing

was originally thought to be purely stimulus-driven. However, a growing body of behavioural

research demonstrates that cognitive factors can also influence these processes (Goodhew,

Fogel, & Pratt, 2014; Hein, Rolke, & Ulrich, 2006; Thomas, 2015; Yeshurun & Levy, 2003).

For example, Yeshurun and Levy (2003) demonstrated that *attentional shifting* can have

varying effects on performance on spatial and temporal acuity measures. Here, focussed

shifts of spatial attention were found to improve spatial acuity, but impair temporal acuity.

This was interpreted as spatial attentional shifting enhancing parvocellular and impairing

magnocellular activation. Likewise, Gozli, West, and Pratt (2012) found that hand

positioning can alter performance in spatial and temporal acuity tasks. When participants'

hands were positioned close to the computer screen, performance on the temporal acuity task

was enhanced and decreased on the spatial acuity task, contrasted with the hands being

placed further away from the computer screen. Similarly, the perception of low-spatial-

frequencies is enhanced, and high-spatial-frequencies impaired near the hands under

conditions of low perceptual load (Abrams & Weidler, 2014). Taken together, this suggests

that cognitive factors can alter the relative input of parvocellular and magnocellular neurons

to visual processing.

Table 1. *Defining Characteristics of Magnocellular and Parvocellular neurons.*

| Parvocellular	Magnocellular
Smaller receptive fields	Larger receptive fields
Demonstrate colour opponency	Relatively colour blind
Lower temporal resolution	Higher temporal resolution
Higher spatial resolution	Lower spatial resolution
High-spatial-frequency sensitivity	Low-spatial-frequency sensitivity
Greater sensitivity to higher contrasts	Greater sensitivity to lower contrasts
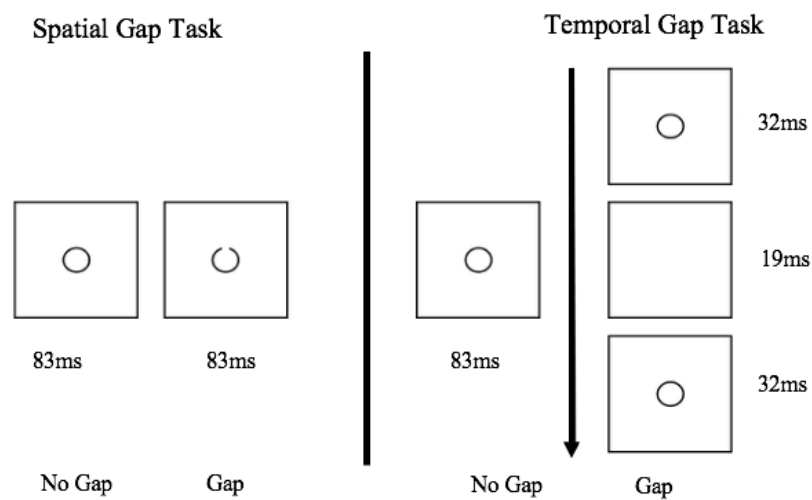
Figure 2. Spatial (left) and temporal (right) acuity tasks. Participants are shown brief presentations of circles and are required to determine whether the presented circle contained either a small spatial or temporal gap.
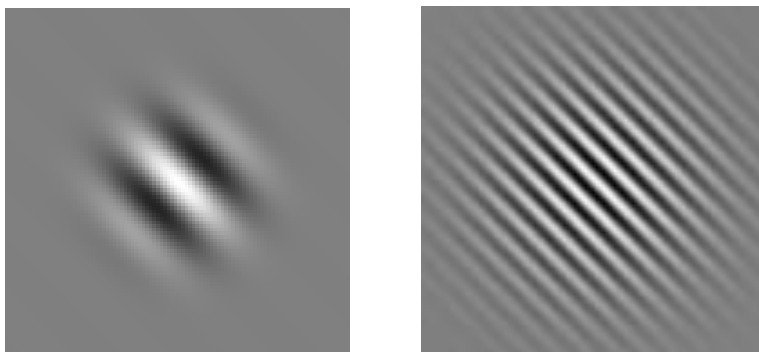

Figure 3. Low (left) and High (right) spatial frequency Gabors. Parvocellular neurons are better versed to process local information (high spatial frequencies). Magnocellular neurons are better versed to process global information (low spatial frequencies).

Based on the differential properties of the visual system, Goodhew and colleagues suggested that attention scaling has different effects on parvocellular and magnocellular mediated processing. Specifically, the SSE account argues that changes in the spatial scale of attention influence parvocellular mediated processing, while having no influence on magnocellular mediated processing. To test this theory, Goodhew et al. (2016) initially explored the effect of scaling on parvocellular related spatial acuity versus magnocellular related temporal acuity. To manipulate spatial attention scale, Goodhew et al. (2016) used a shape inducer task. Specifically, participants determined the identity of briefly presented circles and ovals that were either small (approximately .5 ° radius), hence inducing a small scale of attention, or large (approximately 10 ° radius), inducing a large scale of attention. The effect of attentional scaling on parvocellular and magnocellular activation was then tested using spatial and temporal acuity tasks respectively, that were presented at fixation. Goodhew et al. (2016) found that attentional scaling influenced only parvocellular mediated vision, such that spatial acuity improved with narrow attention, whereas temporal perception was not impacted by the scale of attention.

Furthermore, using a similar shape inducer task to manipulate attention scale, Goodhew and colleagues (2017) demonstrated that performance on a temporal order judgement task, and an orientation discrimination task using low-spatial-frequency stimuli – both magnocellular-mediated aspects of visual perception – were not influenced by attentional scale. This occurred under conditions in which performance on fine detailed spatial tasks (parvocellular mediated) was enhanced by inducing the smaller attentional scale. Further, unlike their original experiment, Goodhew et al. (2017) also varied the eccentricity of the magnocellular related stimuli (spatial and temporal acuity targets), so that they appeared either 2 ° to the left or right of fixation. Critically, presenting targets either to the left or right of fixation introduced a level of uncertainty regarding target location. This was done

to encourage participants to adopt the attentional scale consistent with the intended experimental manipulation. Using this updated methodology, spatial acuity was improved for narrow attention, while no effect was found for temporal acuity.

It is also important to recognise that earlier studies testing attention scaling and perception provide some evidence largely consistent with the predictions of the SSE account. For example, Goto et al. (2001) used a dual-task paradigm to measure attentional scaling and contrast sensitivity thresholds for high and low-spatial-frequency Gabors. The primary task, which manipulated attention scale, required participants to detect changes in patterns which appeared in different sized concentric rings presented around fixation (2.5 ° vs. 5 ° in radius). To measure the effects of attention on the perception of different spatial frequency Gabors, while completing the primary pattern task, participants were also required to report if they noticed a Gabor patch appear at fixation during the task. On trials where the Gabor patch was present, the contrast of the stimulus progressively increased until the participant detected it. Thus, differences in contrast sensitivity for Gabor patches of varying spatial frequency content could be measured. The authors found that contrast sensitivity for lower-spatial-frequency Gabors (i.e., <2 cycles per degree) differed minimally under narrow versus broad attention scales, while compared to broad attention, a small scale of attention improved contrast sensitivity for Gabors of high-spatial-frequency content.

Finally, by testing the effect of attention scaling on global motion perception, there has been some indirect evidence favouring the SSE account (Burnett et al., 2013). Global motion processing is measured behaviourally using Random Dot Kinematograms (RDKs). RDKs are constructed by presenting an array of moving dots, where a subset of dots move coherently, and others move randomly (Edwards & Badcock, 1994; Newsome & Pare, 1988). To perceive motion, the dorsal visual system, and in particular cortical area V5/MT is engaged to pool the motion signals and this area receives most of its input from the

magnocellular system (Denison et al., 2014; Derrington & Lennie, 1984; Goodale & Milner, 1992; Livingstone & Hubel, 1988; Maunsell & van Essen, 1983; Mishkin, Ungerleider, & Macko, 1983; however, see Nassi & Callaway, 2009). Therefore, it is possible that the effects of attentional scaling on motion processing may be linked to the influence of attention on the magnocellular visual pathway.

Recently, Burnett and colleagues (2013) measured the effect of attention scaling on global motion perception. In their study, attention could be oriented using a peripheral, non-informative exogenous cue to one of four possible locations. These four locations contained RDKs, which either consisted of noise dots (3 locations), or a coherent motion signal that was briefly presented amongst noise dots (1 location). Participants had to indicate the direction of coherent motion. Furthermore, on 50% of trials, a red dot-probe appeared at one of the four locations (not necessarily the same location as the motion stimulus). Where relevant, participants indicated in which location the dot-probe appeared. Across trials, cue size changed, such that the cue matched the size of the RDK (11 ° in diameter, the brightening of an annular placeholder), or was smaller and fit inside of the RDK (4 ° in diameter). Consistent with the SSE account, small and large exogenous cues produced equivalent validity effects for the RDK task, though only the small cue produced validity effects for the dot-probe task. This indicates that the size of the cue had little to no effect on global motion processing and suggest that attentional scaling has minimal influence on visual processing related to global motion perception. If one accepts that magnocellular perception may contribute to global motion processing, this provides further converging evidence favouring the SSE account.

Spatiotemporal trade-off account

Although Goodhew and colleagues found that attentional scaling had minimal effects on magnocellular related visual processing, other studies have found that a narrow breadth of

attention can impair magnocellular mediated perception. For example, Mounts and Edwards (2017) used a peripheral cueing task to manipulate attention scale. Here, either an arc of a circle (30 ° to 120 ° segments of circles) or parallel lines (length of 1.25 ° to 6.25 °) of differing sizes were briefly flashed to alert the participant to the general location of an upcoming target. When the cued region was small, it was assumed attention narrowed, and when the region was large, attention broadened. Immediately following the cue, either spatial or temporal stimuli were presented. The spatial and temporal stimuli used were similar to those used by Goodhew et al. (2017, 2016), which can be inferred to tap parvocellular and magnocellular processing. Critically, unlike Goodhew et al. (2017, 2016), Mounts and Edwards found that although narrow attention improved spatial acuity relative to broad attention, it impaired temporal acuity. This suggested that in some cases, rather than having no effect, narrow attention can impair magnocellular mediated perception.

Furthermore, earlier research conducted by Shulman and Wilson (1987) suggests that broadly scaled attention may improve low-spatial-frequency detection. Here, Navon letters were used to manipulate attention as has been done previously (Borst & Kosslyn, 2010; Navon, 1977, 2003). Navon letters are constructed by combining smaller letters to make the shape of one larger letter. Therefore, one can attend to the local level (i.e., the small letters) and determine their identity or attend to the global level to determine the larger letters' identity. When attending to the local letters, it can be assumed that attention is narrowed. In contrast, when attending to global letters, attention is broadly spread. In Experiment 2 of Shulman and Wilson (1987), participants attended to and discriminated local elements (.4 ° x .4 ° in size) or global elements (4.6 ° x 4.6 ° in size) of Navon letters. Alongside this, on 50% of trials, Gabors of varying spatial frequency content were presented with the Navon figure. At the end of the trial, participants were required to state whether the Gabor was present or absent, as well as what spatial frequency content was presented. Critically, in Experiment 2,

when participants attended to the local elements (i.e., narrow attention), detection of the higher-spatial-frequency Gabors improved. However, when they attended to the global elements (i.e., broad attention), detection of the low-spatial-frequency Gabors improved. This implies that while narrow attention improved parvocellular mediated perception, broad attention enhanced magnocellular mediated perception.

That narrow attention could impair performance in low-spatial-frequency, and temporal-gap acuity tasks is also physiologically plausible when considering the constraints of the visual system. Indeed, as an alternative to the SSE account, Goodhew et al. (2016) also proposed the STA. This account suggests that differences in attentional scale may map onto the different receptive field sizes of parvocellular and magnocellular neurons, consequently having varying effects on perception. Indeed, while parvocellular neurons have small receptive fields, magnocellular neurons have relatively larger receptive fields. Narrow attention may preferentially require the smaller receptive fields of parvocellular neurons, enhancing spatial acuity, and impairing temporal acuity, while broad attention would map onto the larger receptive fields, calling on magnocellular input to enhance low-spatial frequency-perception and temporal acuity, while impairing high-spatial-frequency perception and spatial acuity.

Finally, it is worth considering that the relative size difference in attentional manipulations used across the literature may explain some of the discrepant findings supporting the SSE versus STA models of attention scaling. Specifically, one reason why previous research might have found no effects of scaling on magnocellular mediated perception is that the size differences between narrow and broad attention manipulations were too small (e.g., Burnett et al., 2013; Goodhew et al., 2017, 2016; Goto et al., 2001). However, this seems unlikely. For instance, in Mounts and Edwards (2017), in Experiment 2, the small attention inducer lines were 1.25 ° in length, and the large were 6.25 ° in length.

These authors found attention scaling to influence parvocellular and magnocellular mediated processing. In contrast, Goodhew et al. (2016) used inducer stimuli with a larger relative size difference (1 °vs. 20 °in diameter) and found scaling to have no influence on magnocellular mediated processes. Thus, compared to Mounts and Edwards (2017), the much larger relative difference in inducer size in Goodhew et al. (2017, 2016) still resulted in a null effect.

Furthermore, all studies finding null effects of attention scaling on magnocellular mediated processes (i.e., Burnett et al., 2013; Goodhew et al., 2017, 2016; Goto et al., 2001) have still found attention scaling to have influenced other visual processes. In Burnett et al., attention scale was found to influence probe detection. In Goodhew et al. (2017, 2016), scaling influenced parvocellular mediated processes such as spatial acuity. Finally, Goto et al. (2001) found changes in attention scale to influence the perception of high-spatial-frequency stimuli. As such, it appears that relative size differences in attention scale are not a contributing factor to contradictory findings in the literature.

Attentional attraction field account

An alternate explanation for the findings of Mounts and Edwards (2017) is Baruch and Yeshuruns' (2013) AAF account. The AAF was originally developed to explain the functioning of attentional shifts. The primary assumption of this account is that under attentional focus, the receptive fields of cells at different levels of the visual hierarchy converge, and subsequently, overlap one another. This contraction of receptive fields to a single location allows for both increased spatial and decreased temporal resolution. Increases in spatial resolution occur as the overlapping of receptive fields allows for a higher sampling rate of the attended area, and thus, an increased ability to perceive fine detail. In contrast, decreases in temporal resolution occur due to this increased population response of cells converging at the attended location, thereby diffusing a precise temporal signal. Specifically, the increased activation increases the strength and variability of cellular responses at the

attended location, causing a prolonged population response. This makes it more likely that two temporal events in close proximity are perceived as a single event, thus lowering temporal resolution. Therefore, Mounts and Edwards (2017) proposed that instead of differentially influencing parvocellular and magnocellular neurons, in their study, the varied effects of attentional scaling on spatial and temporal resolution may have been due to increased convergence of visual cell receptive fields under narrow, compared to broad attention. That is, narrow attention would attract receptive fields to a smaller, overlapping spatial region, thus increasing spatial acuity, and decreasing temporal acuity. As both the STA and the AAF account both predict the same behavioural outcome via different physiological mechanisms, currently, behavioural evidence is unable to distinguish between the two accounts.

Interim summary

The zoom lens, SSE, STA, and AAF accounts each outline how attentional scaling might influence visual processing. All four accounts of attentional scaling propose that narrowing attention improves performance on parvocellular mediated behavioural tasks, such as spatial gap acuity and letter discrimination. However, the predictions of the accounts diverge when elucidating the role of narrowing attention on performance for magnocellular mediated behavioural tasks. While the zoom lens account argues that narrowing attention improves all aspects of visual processing, more recently developed accounts propose that the effects of attentional scaling on magnocellular mediated perception differ, where narrow attention either has none or a negative impact on low-spatial-frequency perception and temporal resolution. Complicating this, each theory has unique pieces of supporting evidence, all of which demonstrate complex and varied effects of attention on perception. Here, we believe that to fully understand how attention scaling influences vision, the differences in these studies, and their outcomes must be critically analysed. Specifically, the varied effects

found in the literature may be largely due to the distinct methods that each of the studies have used to alter attentional scale. Therefore, in the following section, we focus on evaluating the methodological differences present in key papers supporting each theoretical model so to provide much-needed clarity to the literature.

Methods of Attentional Manipulation

      Endogenous and exogenous attention

      As evident from the above review, the methods used to manipulate and measure the effects of attention scaling on vision are widely varied, and in turn, may contribute to the discrepant effects scaling appears to have on magnocellular mediated visual perception. For instance, all four accounts of attentional scaling and vision are agnostic as to how endogenous versus exogenous scaling might influence vision. This is surprising, as unpacking exactly how endogenous and exogenous scaling might influence perception may provide much-needed clarity to the literature (Mounts & Edwards, 2017).

      Broadly, endogenous, or 'top-down' attention is typically thought of as internally, goal-driven attention and exogenous, 'bottom-up' attention is thought of as externally driven, goal irrelevant attention (Awh, Belopolsky, & Theeuwes, 2012; Carrasco, 2011; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Attentional scaling has been manipulated exogenously using both central and peripheral cueing paradigms, where the size of a briefly presented luminance change is altered to capture and set attention (Greenwood & Parasuraman, 1999, 2004; Greenwood et al., 1997; Jefferies & Di Lollo, 2017; Mizuno, Umiltà & Sartori, 1998; Mounts & Edwards, 2017; Turatto et al., 2000; Umiltà 1998). In contrast, endogenous attention is thought to have a slower time course, be sensitive to manipulations of cognitive load. For example, endogenous attention has been manipulated using central cueing procedures, which indicate the spatial region over which attentional

resources should be deployed for upcoming target detection (Balz & Hock, 1997; Goto et al., 2001; Müller et al., 2003; Poggel et al., 2006; Shiffrin, McKay, & Shaffer, 1976).

Although the dichotomization of attention into endogenous and exogenous factors has proved useful for understanding the dynamics and flexibility of attentional scaling using response time measures (e.g., Benso et al., 1998; Turatto et al., 2000; Umiltà, 1998), it is important to note that there has recently been substantial debate in regards to the utility of this distinction. In particular, Theeuwes and colleagues have argued that rather than considering spatial attention components comprising a dichotomy, instead, they can be considered as a trichotomy: endogenous factors, exogenous factors, and selection history (Awh et al., 2012; Failing & Theeuwes, 2018). Selection history is conceptualised as the enduring influence of attention across time, regardless of top-down and bottom-up attentional forces (Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2018). For instance, Fuggetta, Lanfranchi, and Campana (2009) used visual search arrays of varying sizes to manipulate the spatial scale of attention via selection history. A search array, of a particular size, was repeated over a series of trials. This repetition led to faster processing times in the visual search task when the size of the search array remained consistent. In contrast, when the size of the search array changed, response times for visual search were substantially slower. Likewise, global versus local attention has been reliably manipulated via trial repetition of Navon letters (e.g., Hubner, 2000). Nonetheless, while Theeuwes and colleagues suggest this is a distinct process to endogenous attention, we believe that selection history can suitably be categorised as an element of top-down attention scaling. That is, selection history can be conceptualised as the carryover or hysteresis of an endogenous effect, which takes some time to instantiate (e.g., effects may increase over the first few trials in a block) and does not decay immediately after a goal is removed (Egeth, 2018). Indeed, Egeth argues that rather than separating attentional effects into three separate categories, endogenous and exogenous

attention can be broadly considered to be 'cognitive' and 'perceptual' phenomena, which both have different subclasses, and sometimes differing effects on behavioural outcomes. While changes in the environment may trigger perceptual adjusting of attention, trial repetition, or volitional goals are cognitive mechanisms of attentional adjustment.

Understanding the separate roles of endogenous and exogenous scaling on visual perception is potentially important as parallel literature suggests that when attention is *shifted*, endogenous versus exogenous attention differ in their effect on magnocellular mediated processing (Hein et al., 2006). That is, while exogenous shifts of attention impair magnocellular mediated temporal acuity, endogenous attentional shifting enhances temporal acuity (Hein et al., 2006). Mounts and Edwards (2017) noted that since this exogenous/endogenous distinction is so critical for shifts of attention, there is a distinct possibility that it might also be equally important for attentional scaling. Therefore, understanding how endogenous versus exogenous attentional scaling influences visual perception will help disentangle the circumstances under which narrowing attention scale either improves, has no influence on, or impairs magnocellular mediated processing (Mounts & Edwards, 2017).

Indeed, Mounts and Edwards (2017) recently suggested that endogenous versus exogenous attentional scaling may explain the difference in empirical findings of Goodhew et al. (2016) and their own study. This may provide clarity as to the explanatory power of the SSE and STA accounts of scaling. As shown in Figure 4, Goodhew and colleagues used a shape inducer paradigm to manipulate attention scale. Although the authors did not specify whether their shape inducer paradigm utilised endogenous or exogenous attention, the task may be considered more endogenous than exogenous (Mounts & Edwards, 2017). This is because, on each trial, participants were required to voluntarily interpret form information at different spatial scales (sizes). When inducer shapes were small, to complete the task

correctly, an observer needed to constrain the region over which their attention was spread to a small spatial area. In contrast, when the shapes are large, they must have sustained a wide spread of attention to perceive form differences. Furthermore, the inducer task is completed via a trial repetition. The maintenance of a particular attention scale across time requires effortful, goal-directed cognitive resources (i.e., sustained attentional component to maintain the region over which cognitive resources are deployed). Indeed, early research exploring attention flexibility suggests that while exogenous attention can initially set the size of the attention scale, a sustained cognitive effort is required to maintain a particular attended region size (Turatto et al., 2000).

In contrast, Mounts and Edwards' (2017) peripheral cueing paradigm can be seen as a more exogenous manipulation of attention scale (Figure 5). On each trial, a participant's attention is captured by an external luminance change. It is thus assumed that participants automatically scale their attention to the size of the cued region, regardless of their goal of target detection, which requires relatively less cognitive effort. Indeed, Turatto et al. (2000) found that attention automatically scales to the size of objects presented in the visual field. Further, the time interval between the cue and target is relatively short (i.e., 90ms), thus necessitating the use of faster attentional mechanisms. Therefore, it is possible that when a particular scale of attention is sustained, such as in Goodhew and colleagues' studies, there is no impact on magnocellular mediated perception, whereas when attention is scaled exogenously, broadening attention can improve magnocellular related processing. Nonetheless, it is important to recognise that Mounts and Edwards' manipulation may not be a purely exogenous manipulation. In particular, in the study, the cue itself was predictive of the region in which the target would appear in on 100% of trials (although not 100% predictive of the exact target location, nor the size of the attentional cue itself). Thus implicit learning processes might have been involved, see Lanthier, Wu, Chapman & Kingstone,

2015). As such, it would be fruitful for future research to systematically test purely

endogenous versus purely exogenous attention scaling on all aspects of visual perception.

Furthermore, it is important to note that the distinction between endogenous and exogenous

attention scaling as provided by Mounts and Edwards (2017) is unable to account for all

attentional scaling effects on vision. While sustaining a particular scale of attention had no

influence on magnocellular mediated perception in Goodhew et al. (2017, 2016), there are

cases where sustaining either a narrow or broad scale of attention scale has altered

magnocellular mediated processing. For example, in contrast to Goodhew and colleagues,

Poggel et al. (2006) found narrow attention to improve temporal resolution. Recall that in this

study, participants were conducting an endogenous visual search for a double pulse target in

an array of nine lights. The authors found that broad attention impaired temporal sensitivity.

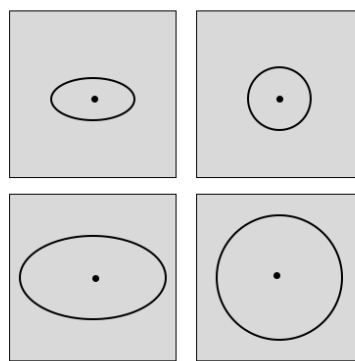Similarly, Shulman and Wilson's (1987) Navon letter study found that broad attention can

Figure 4. Shape Inducer Task used by Goodhew and colleagues (inducer sizes not to scale).

The participant's task is to determine the shape presented on a trial by trial basis at either a

small (top) or large (bottom) spatial scale. Inducer size was blocked so that participants

would adopt either a narrow or broad focus of attention across a series of trials.
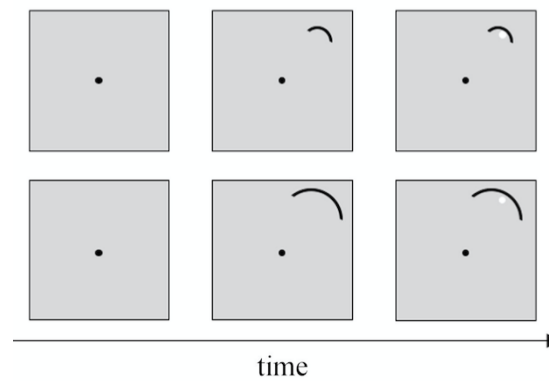
Figure 5. The peripheral cueing task used by Mounts and Edwards (2017). Each trial, participant's attention was cued to either a small or broad region of the visual field via a brief luminance change (cue), which varied in size. A small cue condition is presented in the top three panels, whereas a large cue condition is presented in the bottom three panels. Following the cue, the target, either a spatial or temporal acuity target appeared.

improve magnocellular-mediated perception. Here, participants had to both complete a Navon letter task, while also monitoring spatial-frequency Gabor probes. Broad attention improved performance for the detection of low-spatial-frequency stimuli targets, while narrow attention improved target detection for high-spatial-frequency stimuli. Thus, this task can be seen as largely endogenous, as participants voluntarily attended to either the global or local level of the primary task. As such, rather than concluding that all scaling effects can be accounted for via the endogenous/exogenous distinction, it is important to consider other methodological factors which may mediate this relationship.

Stimuli used to manipulate attention scale

Apart from endogenous and exogenous attention, the particular stimuli used to manipulate attention scale has also varied across studies, and could, in turn, explain the discrepant results for magnocellular mediated perception in the literature. For instance, many

studies employ differently sized unfilled shapes to try and manipulate the scale of attention. Across these studies, the effects of scaling on magnocellular mediated perception have been negligible. For example, recall that in Goodhew et al. (2017, 2016), unfilled shapes differing in size were shown over a series of trials, with the purpose of altering attention scale. These authors found that narrowing attention had no impact on magnocellular mediated temporal acuity or low-spatial-frequency perception. Similarly, Burnett et al. (2013) used differently sized unfilled cues to orient attention to the potential locations of global motion targets. Again, the effects of scaling on the magnocellular related process appeared to be minimal. Finally, Goto et al. (2001) used ring stimuli to alter attention, finding scaling to have no effect on contrast sensitivity for low-spatial-frequency stimuli.

As such, it is possible that previous null findings of attentional scaling and magnocellular mediated visual processing in the literature might be in part due to the use of unfilled shapes to manipulate attention scale. One possibility is that differently sized unfilled shapes might require observers to deploy an annulus of attention (a ring). Although it is unlikely that *all* studies which have used unfilled shapes to manipulate attention scale have caused an annulus distribution of attention, when a given task encourages it, be it via increased task difficulty or spatial structure present in a scene (such as via an unfilled shape), research has found that individuals may distribute attention as an annulus, focusing resources on the edges of the stimuli (Egly & Homa, 1984; Jefferies & Di Lollo, 2015). For example, Jefferies and Di Lollo (2015) measured the influence of centrally presented distracting information on the ability to identify peripherally presented targets. Critically, in one condition, placeholder boxes were present in the visual display, thus providing spatial structure, and in another, they were absent. Overall, accuracy was improved when placeholders were present, suggesting that the spatial structure provided allowed participants to distribute attention as an annulus, and ignore centrally presented distractors. Likewise, it is

possible that in Goodhew et al., (2017, 2016), the difficulty of the shape discrimination task (i.e., identifying fine demarcations in peripherally presented stimuli), demanded an annulus distribution of attention for effective processing. Indeed, when a task is sufficiently difficult (such as the shape inducer task), it is likely that participants might alter the shape of attention, rather than scale attention to meet task demands effectively.

Therefore, for studies such as Goodhew et al. (2017, 2016) that attempt to manipulate attention using unfilled shapes, it is possible that the different types of attentional deployment used by participants (i.e., an annulus distribution of attention), may not influence magnocellular mediated vision in the same manner that attention scaling does. This would imply that the selective spatial enhancement model may only apply to an annulus distribution of attention. For example, in Goodhew and colleagues (2017, 2016), if an annulus of attention was deployed, then for the small shape inducer condition, cells located at the fovea would be activated, whereas for the large inducer, only cells in peripheral vision would be activated. Critically, there is a difference in the relative density of parvocellular and magnocellular neurons across the visual field, where parvocellular neurons are clustered in foveal vision, and magnocellular neurons are located at greater eccentricities (Malpeli, Lee, & Baker, 1996). Therefore, under a small shape inducer, parvocellular neurons would be activated, improving spatial acuity, whereas, for a large inducer, this would not be the case. In contrast, changes in the size of the annulus distribution of attention would not influence performance on the temporal acuity task, as no magnocellular neurons necessary for processing the centrally presented target would be activated. Therefore, the SSE account may not apply to attentional scaling per se, but rather, that it applies to the effect of different sized annuli of attention on perception.

In contrast, studies that have found attention scaling to influence magnocellular mediated processing have used tasks which do not entail an annulus distribution of attention.

Instead, these tasks require attention to be scaled across the visual field. For example,

Shulman and Wilson (1987) used Navon letters, which require an individual to attend to both

the global structure of the shape and smaller local elements simultaneously. Thus, the task

required a somewhat even distribution of attention across the stimulus range. Likewise,

Poggel et al. (2006) required participants to attend to peripheral and central target locations

simultaneously to detect a luminance change in an array of 9 lights. Although the luminance

dots were arranged as an annulus, they do not provide clear edges as unfilled shapes do. As

such, it is likely that to complete the task, participants would have deployed an even

distribution of attention. Finally, although Mounts and Edwards (2017) used shape segments

to manipulate attention scale, because target stimuli appeared along the bounds of these

shapes, it is likely that they fell within the scope of attention. Therefore, it is likely that this

methodology does not fall prey to the same limitations as does the use of unfilled shapes with

centrally presented stimuli. Instead, it appears that when attention scale is manipulated using

appropriate stimuli which do not require an annulus of attention, scaling appears to influence

magnocellular mediated perception (although the direction of this effect appears to vary).

As such, future research should aim to use methods of attention scale manipulation,

which promote an even spread of attention across the entire stimulus region. For instance, a

recent study conducted by Lawrence, Edwards, and Goodhew (in press) tested the effect of

sustained attention on both parvocellular and magnocellular related processing using an

experimental manipulation which would have necessitated an even spread of attention.

Specifically, attention scale was manipulated using small and large global motion stimuli. On

each trial, participants had to determine whether a series of dots were moving in a clockwise

or counterclockwise direction. Because the direction of motion in global motion stimuli

cannot be processed by tracking a single dot, an even distribution of attention is required to

perceive the direction of motion (Edwards & Badcock, 1994). As such, it is highly unlikely

that participants were deploying an annulus of attention in this task. An identical design to that used by Goodhew and colleagues (2017, 2016) was used, whereby 80% of trials were attention inducer trials (i.e., Motion stimuli that were small or large in size), and 20% of trials contained spatial and temporal acuity tasks. Using this novel experimental method, the authors found narrow attention to improve both spatial and temporal acuity. This provides strong evidence that sustained attention scaling has similar effects on parvocellular and magnocellular processing, thus providing support for the zoom lens model of attention. As such, future research should check whether the methods used to manipulate attention scale might inadvertently cause an annulus of attention.

Task complexity

Although the particular type of stimulus used to manipulate attention scale is able to account for a large majority of null findings in the literature, it is still evident that studies which do not adopt unfilled shape stimuli still have somewhat conflicting findings. In particular, while Shulman and Wilson's (1987) and Mounts and Edwards' (2017) research indicates that narrowing attention scale impairs magnocellular mediated visual processing, Poggel et al. (2006) found evidence that narrowing attention can improve magnocellular mediated perception. Both of these studies used a method of attentional manipulation that likely requires an even distribution of attention, rather than an annulus distribution because, in these studies, participants were required to attend to both central and peripheral locations in the visual field simultaneously. Therefore, in the following section, we discuss one possible factor which future research may use to disentangle these discrepant findings: task complexity.

The difficulty of an experimental task may influence how attention is scaled, and therefore, the effect of attention on different channels of visual perception (Caparos & Linnell, 2010; Lavie, 1995, 2005; Lavie, Hirst, De Fockert, & Viding, 2004; Linnell &

Caparos, 2011, 2013; Parks, Beck, & Kramer, 2013). Specifically, task complexity can be operationalized via differences in the overall amount of perceptual and cognitive load placed on a participant while completing a task, where higher amounts of perceptual and cognitive load lead to greater task complexity. Perceptual load refers to the complexity of visual stimuli and information to be processed in a scene (Lavie, 1995; Linnell & Caparos, 2013). For example, a visual search where distractors show little similarity to the target may be considered a low perceptual load task, and a search where distractors are heterogeneous and similar to the target may be considered a high perceptual load task (e.g., Roper, Cosman, & Vecera, 2013). In contrast, cognitive load can be thought of as the amount of cognitive/intellectual resources required to complete a task. For example, a high cognitive load task may require participants to complete a complex mathematical equation, and a low cognitive load task may require participants to complete a simple equation (Lavie et al., 2004).

Changes in both perceptual and cognitive load are thought to have differing effects on attentional scaling. For example, some research suggests that high levels of perceptual load cause attention to narrow (Chen & Cave, 2013; Lavie, 1995; Theeuwes, Kramer & Belopolsky, 2004). Figure 6 demonstrates a perceptual load manipulation used in a seminal study by Lavie (1995). Typically, the participant's task is to identify the central letter in the display, while distractors that are either the same or different to the target are displayed in the periphery. Under levels of low perceptual load, the distractor letter interferes with the processing of the target letter, where target discrimination response times are slower. In contrast, under high perceptual load, the distractor letter has minimal influence on central letter processing. This suggests that while low perceptual load leads to a broader scale of attention, higher perceptual load leads to attentional narrowing. This is because a narrower

scale of attention should reduce distractor processing, and thus result in faster processing speeds.

Nonetheless, it is important to recognise that the perceptual load account of distractor processing is not universally accepted. Instead, a dilution account has been proposed (e.g., Benoni & Tsal, 2010; Tsal & Benoni, 2010). For example, for Lavie (1995), the dilution account would argue that the key factor driving differences in performance across the high and low perceptual load conditions is the level of dilution between distractor letters across the two conditions in Lavie (1995). For example, in Figure 6, compared to the low load condition, in the high load condition, the effect of the peripheral distractor on target processing may be weakened as distractor processing is spread between the peripheral distractor and the letters surrounding the target, compared to being spread between only the target and the distractor. Therefore, rather than 'high load' conditions causing a narrowing of attention, it is possible that attention is distributed in a similar manner in both conditions. However, it is important to note that task complexity can be varied without using perceptual load paradigms similar to that used by Lavie (for a review, see Murphy, Groeger, & Green, 2016). Here, we consider perceptual load as simply a factor of task complexity, driven by perceptual changes in the tasks themselves. For example, when trying to read tiny letters on a page (a perceptually demanding task), one would narrow attention in, compared to if a task demanded less effort (such as reading larger letters on a similar-sized page. This is a cornerstone of the Zoom lens account, namely, that attention scales relative to task demand (Eriksen & James, 1986).
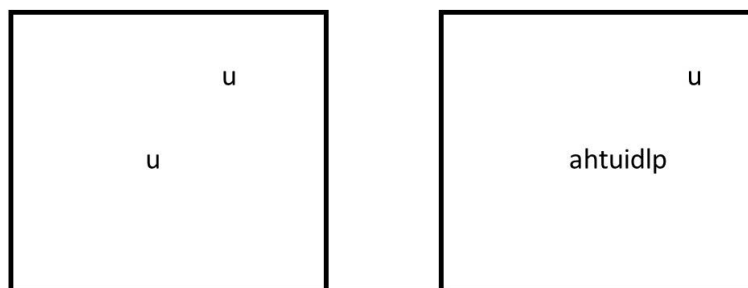
Figure 6. Example of a low (left) and high (right) perceptual load display adapted from the original studies of perceptual load theory (Lavie, 1995). Participants would be asked to identify the presence or absence of the target letter (u) shown at the middle of the display.

Changes in cognitive load have also been proposed to have the opposite effect on attentional scaling. For example, while completing a task similar to that shown in Figure 6 (left), changes in working memory load were found to alter the level of distractor processing. Here, before completing the perceptual task, participants were required to remember either 1 (low load) or 6 digits (high load). After the perceptual task, participants were shown another number and were asked to indicate if they were previously shown that number. Critically, it was found that distracting letters interfered with central target processing to a greater degree in the high cognitive load condition, indicating a broad scale of attention, compared to the low load condition (Lavie et al., 2004). Finally, more recent research has demonstrated an interactive effect between cognitive and perceptual load, and the spatial scale of attention (Linnell & Caparos, 2011). Taken together, the empirical evidence to date strongly indicates that either increasing perceptual or cognitive complexity may alter the spatial scale of attention. Therefore, the differing effects of scaling on magnocellular mediated processing in attentional scaling studies might be at least partly due to differences in task complexity. As such, future research may benefit from utilising tasks where task complexity is systematically manipulated. Importantly, we are not suggesting that increases in the number of distractor

targets be the only method to increase task difficulty. Instead, other methods, which control

for dilution, may be used to alter the scale of attention. Similarly, working memory tasks

could be used to alter cognitive load.

Stimulus eccentricity

Apart from differences in task complexity, the use of central versus peripheral

stimulus presentation can unduly influence the dynamics of attentional scaling and may

account for a large degree of inconsistency in the literature regarding magnocellular mediated

processing. Indeed, the use of central versus peripheral stimuli has several implications for

attention scaling and vision. Firstly, compared to central stimulus displays, presenting stimuli

in the periphery requires an attentional *shift*, as well as a change in attentional scale. For

example, recall that in Mounts and Edwards (2017), attention is manipulated exogenously

using a peripheral luminance cue of different sizes. On 100% of trials, the cue predicts the

location in which the target to be detected will fall. This allows the authors to measure the

effect of a small and large scale of attention on perception. Critically, however, this method

also requires that participants shift their attention as well as scale it. Because the cue always

indicates the target location (i.e., only valid cues are used), this means that the potentially

separate effects of shifting and scaling attention cannot be separated using this paradigm.

Indeed, the conflation of attentional shifting and scaling is particularly problematic, as

attentional scaling and shifting are independent mechanisms, showing different time courses,

as well as having unique effects on visual perception (Benso et al., 1998; Castiello & Umiltà,

1990; Hein et al., 2006; Turatto et al., 2000; Yeshurun & Levy, 2003). For example, recent

work shows that focusing versus shifting attention differentially influences the perception of

crowding in central versus peripheral visual field (e.g., Albonico, Malaspina, Bricolo,

Martelli, & Daini, 2016). Therefore, future research should aim to present attentional cues

centrally or, alternatively, use both invalid and valid cues in exogenous cueing tasks so to separate the effects of attentional shifting versus attentional scaling on visual perception.

In contrast to utilizing a single peripheral cue to attract attention, some researchers have attempted to measure attention scaling using peripherally presented stimuli that appear on both sides of the visual field simultaneously (e.g., Hüttermann & Memmert, 2017). Here, participants fixate on the centre of the visual field. Following this, two target arrays comprising four shapes each are presented at equal eccentricities from fixation. The eccentricity of the shapes is altered to measure attention scale. Following stimulus presentation, participants have to report some information about the properties of the shapes at both locations. It is assumed that to complete the task accurately; the participants must scale attention to the two groups of shapes, allowing the researchers to map the bounds of attention. As such, unlike the presentation of single stimuli in peripheral vision, the use of multiple stimulus locations may negate the use of attentional shifting.

Nonetheless, given that in the Hüttermann task, observers need only attend to the two locations encompassing shapes, it is possible that observers may split attention to the two locations simultaneously, rather than scaling attention across the empty region in between the shapes (e.g. Castiello & Umilta, 1992; Gabbay, Zivony, & Lamy, 2019; McMains & Somers, 2004; Muller et al., 2003, although see Jans, et al., 2010). For example, McMains and Somers (2004) demonstrated that when conducting difficult discrimination tasks at multiple locations simultaneously, activation in the visual cortex is also split. Here, rapid serial visual presentation (RSVP) streams containing letters and numbers were displayed in the four quadrants of the computer screen. Further, one stream consisting only of numbers was presented centrally. During the experiment, participants attended to two of the streams and detected the number stimuli that were interspersed with the letter stimuli. Overall, changes in neural activation, as measured by fMRI, suggested participants split their attentional

resources to two separate locations. Specifically, activation levels changed at the attended location, while no effect was observed at foveal locations, where central distractor numbers were presented. This suggests that observers were able to ignore this central information and deploy attention to non-continuous locations in space. Therefore, when task difficulty permits, it is possible that participants split attention to the separate target locations, rather than scaling attention accordingly.

Secondly, apart from conflating attentional scaling and shifting, studies using peripheral cueing procedures typically manipulate target uncertainty (for example, Mounts & Edwards, 2017 peripheral cueing procedure). While it is possible that target uncertainty may encourage attention scaling, it is possible that by presenting stimuli peripherally to manipulate target uncertainty, rather than observers adjusting their scale of attention to the size of a cued region, an observer may adopt a smaller sized attention scale to the area cued and shift their attention within the cued region to find a target. This would mean that instead of measuring the impact of attention scaling on perception, the influence of search array size becomes the variable of interest. Indeed, the null findings of attention scaling on temporal acuity observed in Goodhew et al. (2017), when target location uncertainty was manipulated, suggests that location uncertainty may not be sufficient for attention scaling. Thus, an experimental manipulation which lowers the variance of target uncertainty by presenting stimuli centrally allows for a cleaner measurement of attentional scaling effects. Alternatively, target uncertainty could be held constant across both small and large attentional scaling conditions. This is because it minimizes the chance that each participant uses a different strategy to complete varying task conditions.

Furthermore, it is important to note that comparing the data between attentional scaling studies which present stimuli either centrally or peripherally may be inappropriate, as peripheral stimulus presentation is more likely to engender a larger proportion of eye

movements, compared to central stimulus presentation. This is particularly problematic for studies measuring attentional scaling effects on magnocellular related tasks that do not control or record saccades. When making eye movements, the visual system can have decreased sensitivity to magnocellular input (i.e., saccadic suppression; Burr, Morrone, & Ross, 1994; Krekelberg, 2010). Given that high-frequency temporal resolution requires a large amount of magnocellular input, eye movements should be minimised or controlled for in attentional scaling studies. Doing so will allow for cleaner conclusions regarding attention and visual processing more generally.

Finally, it is important to note that there are some advantages in using peripheral rather than central displays when testing parvocellular versus magnocellular perception. In particular, there are differences in the concentration of parvocellular and magnocellular neurons in central versus peripheral vision, where more parvocellular neurons are located in central vision, and more magnocellular neurons in peripheral vision (Malpeli et al., 1996). Therefore, to test the effects of scaling on magnocellular vision, it may be more appropriate to present target stimuli in the periphery, where relatively more magnocellular neurons are concentrated. Nonetheless, a number of studies have found attention scaling to influence performance on magnocellular mediated tasks, where stimuli are presented centrally. For instance, Shulman and Wilson (1987) found broad attention to improve perception of low-spatial-frequency Gabors. Likewise, Carmel et al. (2007) found broad attention to improve temporal resolution for a centrally presented light. Finally, Poggel et al. (2006) found that double-pulse resolution was improved under narrow attention, for a centrally presented temporal stimulus. As such, although peripheral presentation may be optimal for studying magnocellular related processes, it appears by no means necessary to observe experimental effects.

Summary

The above analysis illustrates that although attentional scaling effects on parvocellular related processing (e.g., spatial acuity) are somewhat consistent, the effects of scaling on magnocellular related processing (e.g., temporal acuity) are more complex. Critically, current accounts of attentional scaling—The zoom lens, SSE, AAF, and STA accounts—all make differing predictions as to how magnocellular vision is affected, and different studies have provided support for each of the accounts. Here, we have demonstrated that much discrepancy in the literature can be explained by considering the use of unfilled shapes to manipulate attention. Furthermore, we have also discussed the potential roles of endogenous and exogenous attention, task complexity, and stimulus eccentricity on the specific effect scaling has on magnocellular improvement (or impairment). While it cannot yet be claimed that changes in endogenous versus exogenous scaling, task complexity, and eccentricity cause either magnocellular impairment or enhancement, we believe that a systematic, experimental exploration of these factors will provide a full understanding of exactly how scaling influences all aspects of visual perception.

Finally, it is noteworthy that attentional scaling can be altered via a number of individual factors. A substantive body of research has found that working memory capacity, age, mood, personality, culture, and sports expertise can all influence preferred attention scale (e.g. Boduroglu & Shah, 2017; Boduroglu, Shah, & Nisbett, 2009; Hüttermann & Memmert, 2015; Hüttermann, Memmert, & Simons, 2014; Kosslyn, Brown, & Dror, 1999; Kreitz, Furley, Memmert, & Simons, 2015; Lawrence et al., 2018; Wilson, Lowe, Ruppel, Pratt, & Ferber, 2016). Therefore, future research should explore whether the relationship between scaling and perception is consistent for these different groups. For example, a recent study conducted by Boduroglu and Shah (2017) explored whether cultural background influences attentional scaling and spatial resolution. Chinese and American participants

completed a functional field of view task, where accuracy and response times to detect targets at differing eccentricities were measured. It was found that Americans were better able to localise targets, suggesting they adopted a narrow distribution of attention for enhanced resolution.

Attentional scaling is a fundamental cognitive process, allowing us to narrow our cognitive resources to relevant locations in the visual field while filtering out sensory noise. Early accounts of attentional scaling assumed that narrowing attention unequivocally improves visual processing; however, accumulating evidence indicates the relationship between spatial attention and visual perception has far more complexity. Here, we argued that to fully understand attention scaling, the neural pathways involved in visual processing; endogenous versus exogenous attention; the particular stimuli used to manipulate attention, task complexity; and stimulus eccentricity all must be considered conjointly. This is because these factors combine to create unique influences of attentional scaling on vision. Based on these complexities, future research should aim to carefully demarcate the roles of these factors in scaling and vision.

Open Practice Statement: There is no experimental material, data or statistical analyses available with this manuscript.

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