

The impact of scaling rather than shaping attention: Changes in the scale of attention using global motion inducers influence both spatial and temporal acuity.

Rebecca K. Lawrence^{1,2}, Mark Edwards¹, and Stephanie C. Goodhew¹

1. The Australian National University

2. University of Toronto

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Corresponding Author: Rebecca K. Lawrence

Address: Department of Psychology, University of Toronto,
100 St. George Street, Toronto, ON M5S 3G3

Phone: 416-978-6587

Email: rebecca.lawrence@utoronto.ca

Abstract

Originally, the zoom lens model of attention scaling proposed that narrowing attention to a small area of the visual field improves visual perception (Eriksen & James, 1986). A large body of empirical evidence supports this model, showing that narrow attention enhances performance in spatial acuity tasks. Despite this, the zoom lens model does not explicitly consider how attention scaling influences different elements of vision, for example, temporal processing. More recent models of attention scaling suggests that attentional scaling has different effects on spatial and temporal acuity (Goodhew et al., 2017, 2016). However, the evidence to date supporting these models has had one major pitfall: different sized *unfilled* shapes are presented in an attempt to focus attention in or spread it out broadly. This method is problematic because participants may not spread their attention across the entire region defined by unfilled shapes, instead, attending to only the annulus region of the shape. To address this, we developed a new method to manipulate attention, one which requires the pooling of information across the entire stimulus, not just around the outer border. We then tested the influence of attention scaling on perception using spatial and temporal gap tasks. Across two experiments, we found that sustaining a narrow attention scale improved both spatial and temporal acuity. These findings challenge recent research suggesting that attention scaling has differential impacts on spatial and temporal processing, instead supporting the zoom lens model, proposed over 30 years ago.

Keywords: Visual Attention, Spatial Attention, Vision, Zoom Lens Model

Public Significance Statements:

1. Narrowing the region over which attention is deployed in space improves the processing of both fine spatial and temporal information.
2. The use of different sized unfilled shapes to manipulate the area over which attention is spread in space should be avoided. This is because unfilled shapes might cause attention to be deployed as an annulus (i.e. a doughnut shape).

The impact of scaling rather than shaping attention: Changes in the scale of attention using global motion inducers influence both spatial and temporal acuity.

Humans use spatial attention to filter visual information, triaging certain stimuli for enhanced processing while suppressing others (Desimone & Duncan, 1995; Posner, 1980). Here, we were interested in understanding how changing the *scale* of attention influences perception; that is, the effect of sustaining a broad or narrow distribution of spatial attentional resources across the visual field (Eriksen & James, 1986; Eriksen & Yeh, 1985; Greenwood & Parasuraman, 1999; 2004). Note that attentional *scaling* is a distinct form of attentional regulation to *shifting* the centre of the attended location (covert shifts of attention, e.g. Carrasco, 2011; Posner, 1980) or *splitting* attention to multiple regions simultaneously (e.g. Castiello & Umiltà 1992).

Eriksen's zoom lens model proposed that narrowing attention enhances all aspects of perceptual processing (Eriksen & James, 1986; Eriksen & Yeh, 1985). In particular, the model does not specify whether or not attention scaling has different effects on different types of visual perception, and therefore, it can be inferred that the model predicts that the benefit of narrowing attention applies to all aspects of visual perception. There is a large body of behavioural evidence supporting the zoom-lens model, where narrow attention has been found to improve target detection response times and spatial resolution (e.g. Balz & Hock, 1997; Castiello & Umiltà 1990; Eriksen & James, 1986; Eriksen & Yeh, 1985). Furthermore, compared to broad attention, Müller, Bartelt, Donner, Villringer and Brandt (2003) have found narrowing attention to increase the intensity of activation in the primary visual cortex.

Nonetheless, most of the studies that have obtained evidence in support of the model have used visual stimuli that require the processing of fine-grained spatial information. While the

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ability to resolve rapid changes in luminance across space is an important aspect of perception, perception involves more than fine spatial acuity. For example, temporal acuity is another important aspect of perception – that is, the ability to resolve rapid changes in luminance across time. While only a handful of studies have explored the influence of attentional scaling on temporal processing, they have found conflicting results (e.g. Goodhew, Lawrence, & Edwards, 2017; Goodhew, Shen, & Edwards, 2016; Mounts & Edwards, 2017; Poggel, Treutwein, Calmanti, & Strasburger, 2006).

The distinction between spatial and temporal acuity is critical because spatial and temporal detail are thought to be processed by two somewhat separable visual channels: the parvocellular and magnocellular channels respectively. Compared to magnocellular neurons, parvocellular neurons have on average smaller receptive fields and increased responsivity to colour and fine spatial detail but are less responsive to high temporal frequencies. In contrast, magnocellular neurons have larger receptive fields and are more responsive to low spatial frequency, coarse information, as well as higher temporal frequencies (e.g. Denison, Vu, Yacoub, Feinberg, & Silver, 2014; Derrington & Lennie, 1984; Merigan, Katz, & Maunsell, 1991; Nassi & Callaway, 2009; Schiller & Logothetis, 1990; Schiller, Logothetis, & Charles, 1990). While there is considerable overlap in the responsivity of these two classes of cells, stimuli that demand very high spatial or temporal acuity in order to be resolved are thought to be preferentially processed by parvocellular and magnocellular neurons respectively. This means that while in real-world visual processing the two visual streams interact to produce a coherent percept of the outside world; parvocellular neurons likely underlie our ability to perceive fine-spatial information, and magnocellular neurons likely underlie our perception of fine-temporal information (Goodhew et al., 2017). While there is some conjecture regarding whether

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parvocellular and magnocellular processing is separable using behavioural tasks (e.g. Skottun, 2013), there is a wealth of evidence refuting these claims (see Butler et al., 2007; Goodhew et al., 2017 for reviews). Specifically, when tested at the extremes, temporal acuity processes are best subserved largely by the magnocellular channel and spatial acuity processes largely by the parvocellular channel. That is, they are said to predominantly mediate spatial and temporal acuity respectively. Therefore, it is possible that most research on attention scaling and perception have examined the effect of attention scaling on spatial acuity tasks, likely requiring predominately parvocellular processing, and not temporal acuity tasks, likely requiring predominately magnocellular processing. It is therefore unclear whether the effect of scaling would be similar for performance in tasks potentially mediated by both visual pathways.

To date minimal work has been done to explore the effect of sustaining a particular attention scale on temporal resolution (Goodhew et al., 2017, 2016, Poggel et al., 2006). Firstly, early research found narrowing attention to improve temporal resolution (Poggel et al., 2006). In this study, participants completed a visual search for a temporal target appearing in either a small or large-sized search array. When the search array was small, it was assumed that participants would narrow attention to the size of the search array, whereas when the search array was large, they would broaden attention. Furthermore, the size of the search array was kept constant across blocks of the experiment, thus requiring sustained attention at a particular spatial scale. Participants' ability to detect the flickering target was measured by varying the duration of the flicker of one of the potential search targets. Thresholds to detect the flickering target in this search array were lower in the small array condition (i.e. improved resolution).

In contrast to this, Goodhew et al. (2016) recently found changes in sustained attention scale to have no effect on temporal resolution. Goodhew and colleagues used a shape inducer

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paradigm to measure the influence of scaling on both spatial and temporal perception. On the majority of trials, a primary shape inducer task was used to alter the scale of attention, whereby participants discriminated between circles and ovals that were either small, which were intended to induce a narrow attention scale, or large, which were intended to induce a broad attention scale. Similar to Poggel et al. (2006), because the size of the shape inducers was blocked, participants were encouraged to sustain a particular focus of attention within an experimental block. On the minority of trials intermixed amongst the majority trials, a secondary spatial or temporal-acuity task then probed the subsequent effect of attentional scaling on visual processing. It was assumed that the spatial and temporal tasks tapped into parvocellular or magnocellular related processing, respectively (Figure 1).

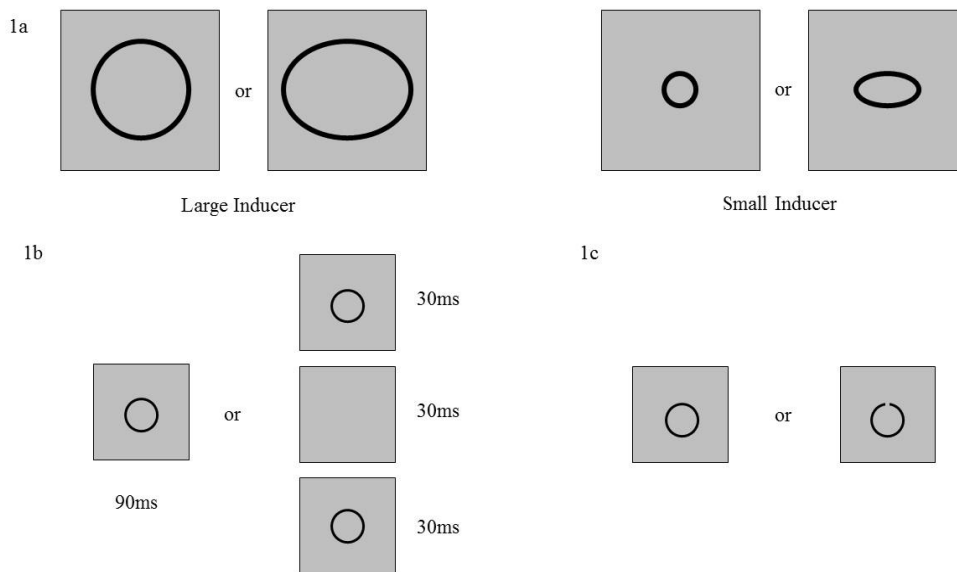


Figure 1. Schematic of the attentional inducer task (a), the temporal gap task (b), and the spatial gap task (c), used in Goodhew et al. (2016). For the inducer task, on each trial, participants are required to determine whether a circle or oval are presented, where small shapes are intended to narrow attention, and large shapes are intended to broaden attention. Interleaved with the shape

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inducer task, are the critical spatial and temporal gap tasks thought to tap into predominantly parvocellular and predominantly magnocellular mediated processing. [Figure adapted from both "Selective spatial enhancement: Attentional spotlight size impacts spatial but not temporal perception", by S.C. Goodhew, E. Shen, and M. Edwards, *Psychonomic bulletin & review*, 23\(4\), p. 1152, Copyright 2016 by Elsevier, and "Testing the generality of the zoom-lens model: Evidence for visual-pathway specific effects of attended-region size on perception", by S.C. Goodhew, R.K. Lawrence, and M. Edwards, *Attention, Perception, & Psychophysics*, 79\(4\), p. 1146. Copyright 2017 by Elsevier. Adapted with permission.](#)

Goodhew et al. (2016) found that when a small shape inducer was used, participants' performance was enhanced for the spatial gap task relative to when a large shape inducer was used. However, performance on the temporal gap task remained unaffected. When considered in relation to the properties of parvocellular and magnocellular neurons, this suggests that attentional scaling only influences performance on tasks predominantly mediated by parvocellular neurons. To account for these findings, Goodhew and colleagues proposed a new model: selective spatial enhancement. According to this model, the primary role of attentional scaling is to increase the spatial resolving power of the visual system, and thus, attentional scaling only acts on the visual channel predominantly responsible for this capacity, i.e. parvocellular neurons (Goodhew et al., 2017, 2016).

The use of unfilled shape cues or segments of shapes to manipulate spatial attention is widespread (e.g. Burnett, d'Avossa, & Sapir, 2013; Greenwood & Parasuraman, 1999, 2004; Mizuno, Umiltà & Sartori, 1998; Turatto et al., 2000; Yeshurun & Carrasco, 2008). However, there is a possibility that shape-inducer tasks used in past research do not directly manipulate attentional scale in the way assumed by the researchers. For example, as shown in Figure 2, in

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Goodhew et al. (2016), the shape inducer task requires participants to attend to the boundaries of the objects presented. However, it does not necessarily require them to attend to the spatial region encompassed by the inducer. Instead, participants might attend to the annulus that the inducer shape provides. Indeed, there is mounting evidence that dependent upon task demands, participants are able to split their attentional resources to multiple locations simultaneously, as well as in an annulus shape (Castiello & Umiltà 1992; Egly & Homa, 1984; Jefferies & Di Lollo, 2015; Jefferies, Enns, & Di Lollo, 2014; Lawrence, Edwards, & Goodhew, 2018; Taylor, Bennett, Chan, & Pratt, 2015). As such, it is critically important to use an experimental procedure that we can be more confident results in a change in attentional scale without any other attentional changes, such as shaping attention as an annulus.

Therefore, in the current study, to manipulate attention scale, we used an inducer that required pooling of information over its entire area. Specifically, we used a global-motion inducer stimulus (e.g. Edwards & Badcock, 1994; Hutchinson, Ledgeway, & Allen, 2014; Newsome & Pare, 1988). Global-motion processing involves the pooling of local-motion to perceive coherent global motion. Unlike the form information present in the shape inducer, these motion signals are located across the entire inducer (Figure 2). Specifically, they are created using a field of dots, where a subgroup of dots travels in a global movement pattern, while the other dots move randomly. Further, the same dots do not carry the signal across the entire stimulus presentation. Instead, the signal dots are varied across frames of stimulus presentation to ensure that the participant cannot track a single dot and must pool the local motion information (Edwards & Badcock, 1994; Newsome & Pare, 1988). Therefore, a participant cannot deploy attention as an annulus in order to effectively perform this task; instead, they must spread their attention across the entire stimulus to perceive the motion. In the current study, the

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size of the motion inducer was varied to alter the spatial scale of attention. The majority of trials in a block were motion inducer trials set to a particular size. The minority of trials (randomly intermixed amongst the majority trials) were spatial and temporal gap tasks similar to those used by Goodhew et al. (2016). These trials allowed us to assess the effects of a narrow versus broad sustained attention scale on both spatial and temporal acuity. If the shape inducer task is an effective manipulation of attentional scaling, then we would expect a similar effect of changing the size of the motion inducer on spatial and temporal acuity as seen in Goodhew et al. (2016). That is, we would expect a pattern of selective spatial enhancement, where the small motion inducer improves spatial acuity but has no impact on temporal acuity. However, if the shape inducer is not an effective way to manipulate attentional scale, then we would expect a qualitatively different pattern of results to that observed in Goodhew et al. (2016).

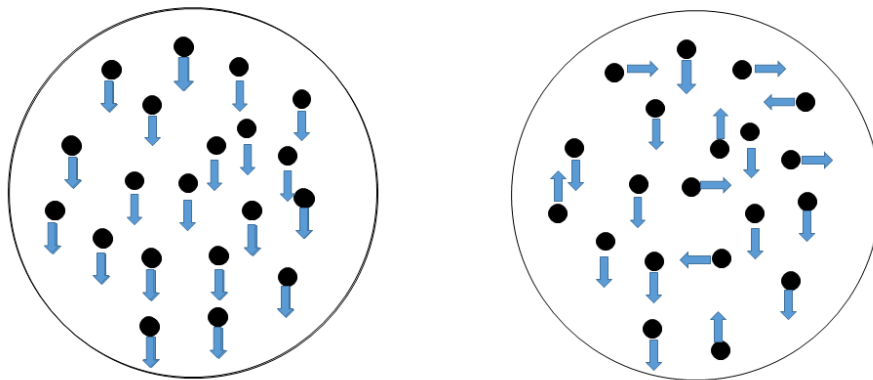


Figure 2. Example of Global Motion Stimuli. In a global motion stimulus, the dots all move in the same direction (100% coherence, left), or only a subset of dots will move in the same direction (50% coherence, right). To perceive motion for a low coherence stimulus, participants must pool information across the spatial area, thus having to spread attention. [Figure adapted from " Global Motion Perception: Interaction of the ON and OFF Pathways ", by M. Edwards](#)

[and D. R. Badcock, *Vision Research*, 23\(4\), p. 2851, Copyright 1994 by Elsevier. Adapted with permission.](#)

Experiment 1

Experiment 1 aimed to test the selective spatial enhancement model of attention scaling using a global motion inducer stimulus of varying sizes to manipulate attention scale. Spatial and temporal acuity tasks were used to test the effect of attentional scaling on different aspects of visual perception.

Method

Participants

Thirty-six (9 male) individuals participated in the study, and their mean age was 24.39 years ($SD = 4.07$). The sample size was determined using Anderson, Kelley and Maxwell's (2017) sample size planner for within-subjects ANOVA. The sample size chosen gave us power = .8, and assurance = .25, to detect an interaction effect similar to that observed in Goodhew et al. (2016). Participants provided written informed consent and received a payment of \$5 (AUD) for participating. All participants reported normal or corrected to normal vision¹. Thirty-four participants were right-handed, and two left-handed.

Stimuli and Apparatus

Stimuli were presented on an LCD monitor with dimensions 475mm by 270mm. Participants were seated and had their head kept stable using a chin rest positioned approximately 600mm away from the monitor. MATLAB, the psychophysics toolbox (Brainard, 1997), and the palamedes toolbox (Prins & Kingdon, 2009) were used to program the experiment. A black fixation dot subtending $.10^\circ$ of visual angle in diameter was presented at the centre of a grey background. The motion stimuli were presented in two different sized circular apertures to

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induce small, and large attention scales, respectively. For each inducer presentation, participants decided whether the signal dots moved in an anticlockwise or clockwise direction by pressing '<' or '>' respectively on a keyboard. The small motion stimulus was designed to narrow attention and had an outer radius of 1.5° of visual angle. The large motion stimulus was designed to broaden attention and had an outer radius of 10° of visual angle. Both had inner radii of $.024^\circ$ of visual angle. The small inducer contained 26 white dots, and the large inducer contained 834 white dots, both with dot densities of approximately $3.68 \text{ dots/degree}^2$. The spatial step was $.19^\circ$, with a dot speed of $5.76^\circ/\text{sec}$. Motion stimuli were presented for approximately 134ms and consisted of 4 distinct motion images presented for approximately 33ms each. On each trial, the signal dot direction was determined randomly.

During experimental blocks of the study, the signal intensity of the motion inducers was determined on a trial by trial basis, where after each participant response, the signal intensity was updated so as to calculate a motion threshold using the PSI method in the palemedes toolbox (Prins & Kingdom, 2009). In turn, this allowed us to estimate a psychometric function for each observer for each experimental block in the study, which quantified performance as a function of stimulus intensity (i.e. the number of signal dots present in the motion inducer). Our task was a two-alternative forced-choice task (are the dots rotating anticlockwise or clockwise?) and the motion threshold calculated in each block estimated the number of signal dots required for an observer to determine motion direction with 80% level accuracy. This ensured that the difficulty of the inducer task was equivalent across different inducer sizes, as well as participants in the experiment.

For the acuity tasks, small white unfilled circles were used. These circles had a radius of 0.19° of visual angle and were centred on the fixation point. For the spatial gap task, on each trial,

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participants had to decide whether the presented circle contained a small $.05^\circ$ gap at the top subtending 0° to 15° from the centre of the circle. The circles were presented for 83.5ms. For the temporal gap stimuli, participants had to determine whether one or two circles were presented successively. If one circle was presented, it was shown for 83.3ms. If two circles were presented, the two circles were presented for 33.3ms each, with a gap of 16.7ms in between. If a gap was present in the stimuli, participants pressed '<' on the keyboard. If no gap was present, they pressed '>' on the keyboard. Once a response had been recorded for either the gap task or the motion task, there was an intertrial interval period of approximately 1000ms².

Design and Procedure

The experiment was a 2 (inducer size: small versus large) x 2 (task: spatial vs. temporal) repeated measures design. There were four experimental blocks consisting of 140 trials each and four practice blocks. Before completing a task for the first time (e.g. spatial acuity task), participants undertook small practice blocks of 10 trials. These practice blocks were interspersed throughout the experiment and were repeated as necessary until participants were familiar with a task (e.g. a participant might complete 20 practice trials for a given task). For the experimental blocks, participants completed one of four possible block order combinations, which were counterbalanced across participants (Table 1). Each of the four experimental blocks consisted of 140 trials. In a block, 80% of trials contained global motion stimuli fixed to be either small or large, and 20% of the trials contained gap tasks, fixed to be either spatial or temporal. Inducer and gap trials were randomly intermixed within a block; however, two gap tasks could not occur consecutively, and the first five trials of each experimental block contained inducer trials designed to set the spatial scale of attention. Participants were offered rest breaks every 70 experimental trials. The experiment took approximately 35 minutes to complete.

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Table 1. *Block order combinations used in Experiment 1.*

	Block Order
1	LS, SS, LT, ST
2	SS, LS, ST, LT
3	LT, ST, LS, SS
4	ST, LT, SS, LS

Notes. Block order was counterbalanced among participants. LS = Large Inducer, Spatial Gap Task. SS = Small Inducer, Spatial Gap Task. LT = Large Inducer, Temporal Gap Task. ST = Small Inducer, Temporal Gap Task.

Results

Exclusion

One participant's data was excluded as they did not complete all four experimental blocks of the study. Further, participants' data were excluded if their accuracy in either the spatial or temporal acuity tasks fell below 60% across both the small and large inducer blocks. Four participants were removed for this reason, leaving a final sample of 31 participants³.

Motion Thresholds

First, threshold estimates for the global motion task in the four experimental blocks were calculated⁴ (Table 2). A repeated-measures ANOVA on motion thresholds indicated that thresholds were higher in the small motion compared to large motion inducer conditions, $F(1, 30) = 16.06, p < .001, \eta_p^2 = .349$. This difference indicates that a greater number of signal dots were required for coherent motion perception in the small inducer condition compared to the large motion inducer condition and is consistent with previous research that indicates that as the

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area of the global motion stimulus decreases, thresholds increase (Hutchinson et al., 2014). Nonetheless, it is important to note that different threshold estimates for the small and large inducer conditions do *not* reflect differences in difficulty across the two conditions. Instead, they reflect the number of dots required in a motion stimulus for an observer to determine the motion direction with an accuracy of 80%. Crucially, this means that the small and large inducer conditions were matched in terms of perceptual difficulty. Furthermore, thresholds did not vary between the spatial and temporal gap task, $F(1, 30) < .01$, $p = .995$, $\eta_p^2 < .001$, nor was there an interaction, $F(1, 30) = 1.93$, $p = .175$, $\eta_p^2 = .060$. Taken together, this indicates that participants were equally engaged with the attentional induction task in both the spatial and temporal gap detection blocks.

Table 2. *Global motion threshold (%) as a function of inducer size and gap task.*

	Small Inducer	Large Inducer
Spatial Task	$M = 28.34$, $SD = 26.02$	$M = 13.11$, $SD = 17.89$
Temporal Task	$M = 25.74$, $SD = 20.55$	$M = 15.73$, $SD = 23.01$

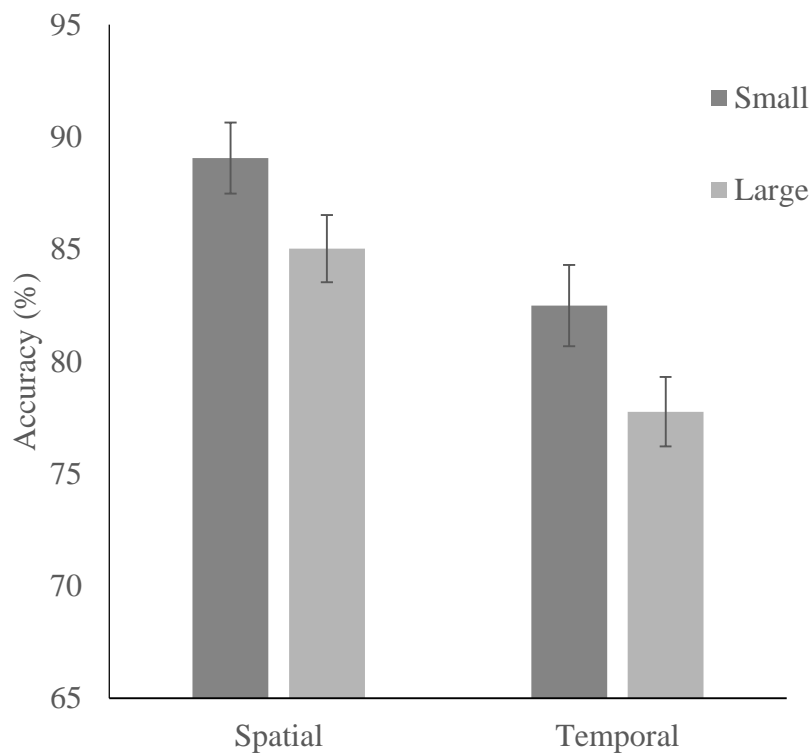
Note. Values reflect the estimated percentage of dots required in each inducer stimulus for coherent motion to be perceived at an accuracy level of approximately 80%.

Spatial and Temporal Acuity Data

Next, the accuracy for the gap detection tasks was calculated. We decided to use accuracy, rather than perceptual sensitivity for our primary dependent variable, as this would allow for a direct comparison between the current study, and Goodhew et al. (2016) previous work. A

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repeated-measures ANOVA was conducted, where inducer size (small vs. large), and gap task (spatial vs. temporal), were within-subject factors. Overall, the effect of inducer size was significant, $F(1, 30) = 5.95, p = .021, \eta_p^2 = .166$. Accuracy in the gap tasks was greater for the small motion stimulus versus large motion stimulus blocks. The effect of gap task (i.e. spatial versus temporal) was also significant, $F(1, 30) = 8.06, p = .008, \eta_p^2 = .212$, where accuracy was higher on average in the spatial compared to the temporal gap task. Critically however, the interaction between inducer size and gap task was non-significant, $F(1, 30) = .08, p = .785, \eta_p^2 = .003, M_{Small\ Spatial} = 89.06 (SD_{Small\ Spatial} = 13.20), M_{Large\ Spatial} = 85.02 (SD_{Large\ Spatial} = 14.06), M_{Small\ Temporal} = 82.49 (SD_{Small\ Temporal} = 14.21), M_{Large\ Temporal} = 77.77 (SD_{Large\ Temporal} = 13.23)$. As shown in Figure 3, this suggests that changes in attentional scale influenced both spatial and temporal acuity, where accuracy was higher in both tasks for narrow compared to broad attention.



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Figure 3. Accuracy (% , vertical axis) in the spatial and temporal gap tasks for the small and large inducer conditions (horizontal axis). Within-subjects error bars displayed (Cousineau, 2005).

Response Time Data

Although accuracy was the primary dependent variable, and the task was unspeeded, mean response time for the spatial and temporal acuity tasks were calculated for the four experimental blocks to check for speed-accuracy trade-offs. Firstly, at the individual level, response time outliers were defined as responses that were less than 200ms, or greater than two standard deviations away from the participant's mean response time across all conditions of the experiment. These outlier data points were removed before group-level analyses. On average, 3.12% of trials from each participant were excluded. Changes in response time over the four blocks was calculated by determining participants' average mean response time for either the spatial or temporal acuity task in each block. Overall, inducer size did not influence response time, where individuals were equally as quick to respond in the small and large inducer blocks, $F(1, 30) = .77, p = .784, \eta_p^2 = .003$. However, there was a main effect of task, $F(1, 30) = 4.83, p = .036, \eta_p^2 = .139$, where participants responded more quickly for the spatial, compared to the temporal acuity tasks across both inducer sizes (Table 3). Finally, there was no interaction between inducer size and task, $F(1, 30) = .54, p = .475, \eta_p^2 = .017$. Taken together, this suggests there was no trade-off in speed versus accuracy for the small versus large inducer size conditions.

Table 3. Mean response time (ms) in the spatial and temporal acuity trials for both the small and large motion inducer conditions.

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	Small Inducer	Large Inducer
Spatial Task	$M = 773, SD = 229$	$M = 781, SD = 238$
Temporal Task	$M = 857, SD = 275$	$M = 832, SD = 205$

Signal Detection Analysis

Finally, in order to gain further insight into how changes in inducer size influenced perceptual sensitivity, a secondary signal detection analysis was conducted on the data (Green & Swets, 1966). For these analyses, where hit rates were 100% or false alarm rates were 0%, scores were replaced with slightly smaller and slightly larger numbers respectively (99.9% and 0.1%). Similar to our accuracy analysis, there was a main effect of inducer size on sensitivity (d'), $F(1, 30) = 5.91, p = .021, \eta_p^2 = .164$, and a main effect of task, $F(1, 30) = 16.30, p < .001, \eta_p^2 = .352$. Furthermore, similar to the observed accuracy scores, there was no interaction between inducer size and task, $F(1, 30) = .03, p = .868, \eta_p^2 = .001$, suggesting that the effect of inducer size on perceptual sensitivity was similar for the spatial and temporal gap tasks. The effect of inducer size, $F(1, 30) = 2.50, p = .124, \eta_p^2 = .077$, task, $F(1, 30) = 1.59, p = .218, \eta_p^2 = .050$, and the interaction between inducer size and task, $F(1, 30) = .03, p = .859, \eta_p^2 = .001$, were all non-significant for criterion (C), suggesting that any response biases that participants may have had were similar across all conditions of the experiment.

Discussion

In Experiment 1, we used a global motion inducer to manipulate attention scale. The method of attentional induction used here had a significant advantage over the previously used shape inducer task. By nature, the motion task encouraged participants to spread attention across the entire region that the stimulus occupied. This contrasts with Goodhew et al.'s shape inducer

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task, where it would have been possible for participants to shape attention as an annulus and attend to only the perimeter of the inducers (e.g. Egly & Homa, 1984). Therefore, using the motion inducer, we can be more confident that participants spread attention across the entire region intended. Critically, we found that narrowing attention scale improved *both* spatial and temporal acuity. This is in contrast to the selective spatial enhancement model, which predicts that changes in attention scale would only influence spatial acuity but not temporal acuity. Instead, the results of Experiment 1 are consistent with the zoom lens model. That is, that narrowing attention scale improved all aspects of visual perception tested.

That a qualitatively different pattern of results was observed in Experiment 1 suggests that the shape inducer previously used by Goodhew et al. (2016) may not have manipulated attentional scale. Instead, using a shape inducer, it appears likely that in Goodhew et al. (2016), participants deployed attention as an annulus. While attentional resources would be most strongly focused at the perimeter of the shape, resources would gradually dissipate around the attended area (i.e. the annulus of focused attention). Therefore, as the distance between the attended region and target changed, the amount of attentional resources falling on the centre of the screen would also vary. This is consistent with the gradient model of attention (LaBerge, 1983; LaBerge & Brown, 1989). If Goodhew et al.'s (2016) manipulation caused an annulus distribution of attention, whereas the current study encouraged attention scaling, it is likely that the two types of attention deployment have different effects on spatial and temporal acuity. That is, while different sized annuli distributions of attention might not influence temporal acuity, narrowing of an evenly spread distribution of attention might improve temporal acuity.

Nonetheless, although the shape inducer task and the global motion inducer task used in the current study differ in their inferred manipulation of attention, it is also possible that the two

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inducer tasks were predominantly processed by different areas of the visual system. These are the ventral visual pathway and the dorsal visual pathway. Although the ventral and dorsal streams are not entirely separate anatomically, and show interconnections, they do appear to differ in their functions, and the types of information they are best suited to process. In particular, the ventral visual pathway is involved in colour and form processing, while the dorsal visual pathway is involved in motion processing and object localisation (e.g. Conway, Moeller, & Tsao, 2007; Goodale & Milner, 1992; Livingstone & Hubel, 1988; Maunsell & Newsome, 1987; Mishkin, Ungerleider, & Macko, 1983; Pasupathy & Connor, 1999). Specifically, in the shape inducer task, participants had to detect small distortions in a circle, and then indicate whether they saw a circle or an ellipse. Object identification, such as that used in the inducer task is a hallmark function of the ventral stream (Mishkin et al., 1983; Wilkinson, Wilson, & Habak, 1998). In contrast, global motion processing has been linked to area V5/MT of the dorsal visual pathway, as it requires the pooling of local motion signals (e.g. Chapman, Hoag, & Giaschi, 2004; Newsome & Pare, 1988).

Therefore, not only did the shape inducer used by Goodhew et al. (2016) and the motion inducer used in the current study differ in their attentional requirements, they also differed in their visual requirements, such that they were likely processed by two different areas of the visual system. Consequently, there are two possible explanations for the discrepancy between the results obtained in Experiment 1 and those obtained by Goodhew et al. (2017, 2016). Firstly, the attentional requirements between the shape inducer and the motion inducer differed. While the shape inducer task might have encouraged an annulus of attention, the motion inducer task was far more likely to require attentional scaling. Secondly, the visual processing requirements of the two tasks also differed. While the shape inducer task potentially required more ventral visual

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input, the motion task potentially required more dorsal visual input. Therefore, the aim of Experiment 2 was to test whether the attentional or visual properties of the motion inducer led to the zoom lens pattern of results observed in Experiment 1.

Experiment 2

Experiment 2 tested whether the zoom lens pattern of results obtained in Experiment 1 was due to either the attentional requirements of the motion inducer or the visual properties of the motion inducer itself. To do so, we developed a Glass pattern inducer stimulus to manipulate attention scale (Glass, 1969). Glass pattern stimuli have similar attentional, but different visual processing requirements to the global motion stimuli used in Experiment 1. In particular, Glass patterns require the ability to pool local orientation signals to perceive form (Glass, 1969; Wilson & Wilkinson, 1998). They are created using a field of randomly placed dots. One or more copies of these dots are geometrically transformed so that pairs of dots (dot dipoles) are arranged to form a global pattern. Importantly, each dot does not provide information about the overall structure of the pattern. Instead, information from dot pairs must be pooled to perceive the pattern. Therefore, similar to the motion inducer, participants are encouraged to spread their attention across the entire stimulus for coherent pattern perception. However, in contrast to the motion inducer used in Experiment 1, Glass patterns require form processing, which is predominately mediated by the ventral visual stream. Thus, Glass patterns are more similar in visual processing requirements to the shape inducers used by Goodhew et al. (2016).

As such, the Glass pattern inducer allows us to disentangle the 'attentional' and 'visual processing' accounts of the pattern of results obtained in Experiment 1. Specifically, if the results of Experiment 1 are driven by attentional mechanisms, in Experiment 2, we expect that changes in the size of the Glass pattern inducer would influence both spatial and temporal acuity.

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However, if the results are driven by the 'visual processing account', it is possible that changes in the size of the Glass pattern inducer would only influence spatial acuity.

Method

Thirty-six (11 male) individuals participated. Of these, 27 were right-handed, three were left-handed, and one was ambidextrous. The mean age of participants was 21.94 years ($SD = 4.65$ years). All reported normal or corrected to normal vision and provided informed consent. \$10 compensation was offered for participation.

The experimental setup and stimuli were identical to that used in Experiment 1, except that Glass patterns, instead of global motion stimuli were used to manipulate the scale of attention (Figure 4). Similar to the motion inducer used in Experiment 1, the small Glass pattern inducer had an outer radius of 1.5° of visual angle, and an inner radius of $.024^\circ$ of visual angle, and contained 26 white dot pairs approximately $.048^\circ$ in size. The large Glass pattern had a diameter of 10° and contained 834 dot pairs. Thus, both inducers had a dot density of 7.37 dots/degree². The signal dots contained either a radial, or a concentric pattern, and were presented for approximately 134ms. Following stimulus presentation, participants decided whether they saw a radial or concentric pattern, by pressing “<” or “>” on a keyboard respectively. Further, the intertrial interval was approximately 1027ms. Overall, the design and procedure of the experiment was also largely similar to Experiment 1 and took participants approximately 35 minutes to complete.

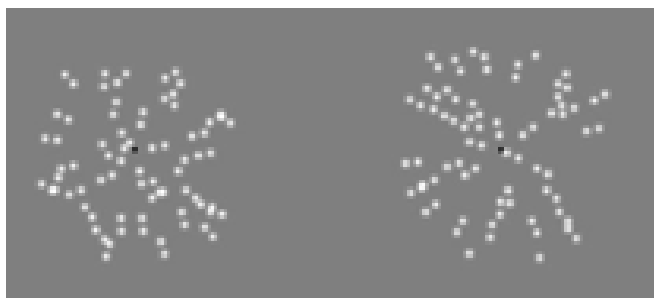


Figure 4. Examples of low coherence (left) and high coherence (right) Glass stimuli containing a radial pattern.

Results

Exclusion Criteria

One participant's data was removed as they did not complete all four experimental blocks. Participant's accuracy data for the spatial and temporal gap tasks were then screened using the same criteria applied in Experiment 1. No outliers were detected. This left a total sample of 35 participants.

Glass Pattern Thresholds

Next, we analysed Glass pattern thresholds for the four experimental blocks. Similar to the motion inducer, Glass pattern thresholds were significantly higher for the small inducer compared to the large inducer, $F(1, 34) = 122.62, p < .001, \eta_p^2 = .783$. As for Experiment 1, it is important to note that the small and large inducer conditions were matched for perceptual difficulty (i.e., an adaptive procedure to produce approximately 80% in both cases). The fact that it took different numbers of dots to achieve this is not problematic, as it is the outcome (perceptual difficulty) that is important. Further, thresholds were similar for both the spatial and temporal gap tasks, $F(1, 34) = .18, p = .676, \eta_p^2 = .005$, and there was no interaction between size and task on overall thresholds, $F(1, 34) = 1.04, p = .316, \eta_p^2 = .030$. Mean thresholds are presented in Table 4.

Table 4. *Glass pattern threshold (%) as a function of inducer size and gap task.*

Small Inducer	Large Inducer

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Spatial Task	$M = 68.57, SD = 15.99$	$M = 35.76, SD = 20.43$
Temporal Task	$M = 71.17, SD = 18.39$	$M = 35.34, SD = 21.47$

Note. Values reflect the estimated percentage of dots required in each inducer stimulus for coherent patterns to be perceived at an accuracy level of approximately 80%.

Spatial and Temporal Processing

To explore the effect of inducer size on spatial and temporal acuity, a repeated-measures ANOVA was run. There was a main effect of size on accuracy, $F(1, 34) = 6.16, p = .018, \eta_p^2 = .154$, such that narrow attention improved performance on both the spatial and temporal acuity tasks. There was a non-significant effect of task, $F(1, 34) = 3.25, p = .080, \eta_p^2 = .087$, where participants were no more accurate in the spatial compared to the temporal gap task. Finally, and crucially, there was no interaction between inducer size and task on performance, $F(1, 34) = .01, p = .898, \eta_p^2 < .001$. Along with the results of Experiment 1, this provides strong converging evidence favouring the zoom lens model. Specifically, in contrast to the process-specific models of attention scaling (i.e. selective spatial enhancement), it appears that maintaining a narrow scale of attention improves both parvocellular and magnocellular mediated processing compared to a broad scale of attention. As shown in Figure 5, accuracy in both the spatial and temporal gap tasks was higher for the small inducer condition compared to the large inducer condition, $M_{Small Spatial} = 88.27 (SD_{Small Spatial} = 13.38)$, $M_{Large Spatial} = 85.41 (SD_{Large Spatial} = 12.05)$, $M_{Small Temporal} = 84.08 (SD_{Small Temporal} = 13.57)$, $M_{Large Temporal} = 80.92 (SD_{Large Temporal} = 14.98)$.

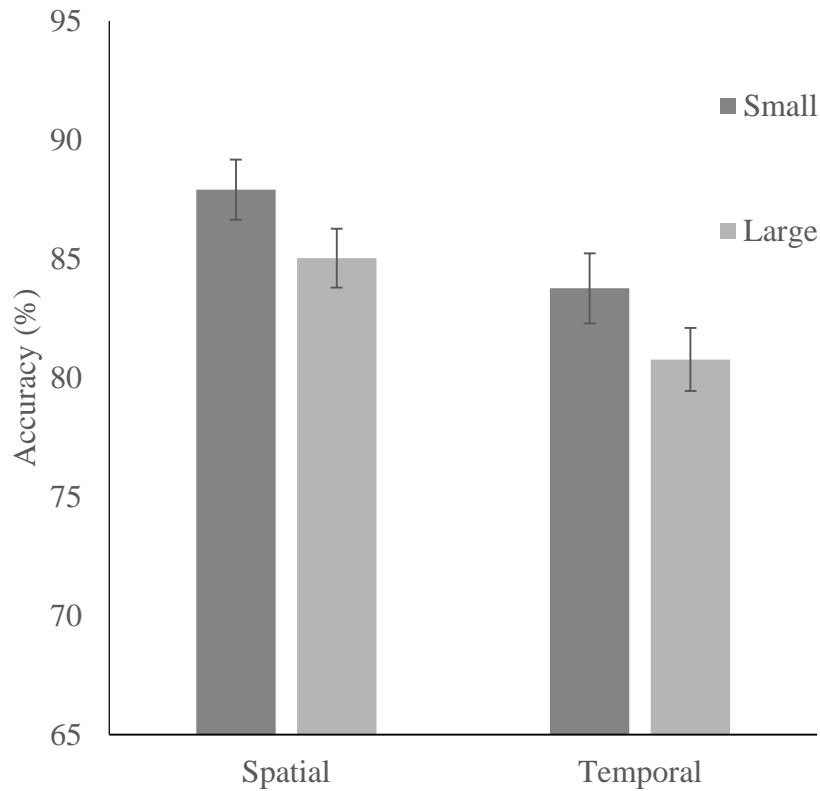


Figure 5. Accuracy (% , vertical axis) in the spatial and temporal gap tasks for the small and large inducer conditions (horizontal axis). Within-subjects error bars displayed (Cousineau, 2005).

Response Time Data

Next, we checked response time data for speed accuracy trade-offs (Table 5). The same RT exclusion criteria used in Experiment 1 were applied, and on average, 3.15% of trials were excluded. Overall, there was no main effect of inducer size, $F(1, 34) = .80, p = .376, \eta_p^2 = .023$, an effect of task, $F(1, 34) = 6.66, p = .014, \eta_p^2 = .164$, and no interaction between inducer size and task, $F(1, 34) = .61, p = .439, \eta_p^2 = .018$.

Table 5. Mean response time (ms) in the spatial and temporal acuity trials for both the small and large motion inducer conditions.

	Small Inducer	Large Inducer
Spatial Task	$M = 735, SD = 264$	$M = 736, SD = 172$
Temporal Task	$M = 801, SD = 191$	$M = 829, SD = 185$

Signal Detection Analysis

Similar to Experiment 1, a signal detection analysis was run on the data obtained in Experiment 2 to gain further insight into how attention influences perceptual sensitivity. Where hit rates were 100% or false alarm rates were 0%, data were replaced with slightly lower or slightly higher scores respectively (99.9% and 0.1%). There was no main effect of inducer size on sensitivity (d'), $F(1, 34) = 1.43, p = .241, \eta_p^2 = .040$, but there was a main effect of task, $F(1, 34) = 4.99, p = .032, \eta_p^2 = .128$. Further, there was no interaction between inducer size and task, $F(1, 34) = .11, p = .742, \eta_p^2 = .003$. The effect of inducer size, $F(1, 34) = .06, p = .804, \eta_p^2 = .002$, task, $F(1, 34) = 4.00, p = .054, \eta_p^2 = .105$, and the interaction between inducer size and task, $F(1, 34) < .001, p = .996, \eta_p^2 < .001$, were all non-significant for criterion (C).

That attention scaling influenced accuracy scores, but not perceptual sensitivity was surprising. Nonetheless, it is important to note that accuracy and sensitivity are not linearly related⁵. As such, future research should directly test the effects of attention scaling on perception using sensitivity, rather than accuracy measures to better understand this relationship. Furthermore, to increase statistical power, we decided to combine the data from Experiment 1 and Experiment 2 and compared differences in perceptual sensitivity and criterion for inducer size and gap task, with inducer type (motion or Glass pattern) as a between-subjects variable. Where hit rates and false alarm rates were 100% or 0%, they were replaced with slightly smaller,

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or slightly larger scores respectively (99.9% and 0.1%). There was a main effect of inducer size on d' , $F(1, 64) = 6.99$, $p = .010$, $\eta_p^2 = .099$, a main effect of task on d' , $F(1, 64) = 19.99$, $p < .001$, $\eta_p^2 = .238$, and no interaction between inducer size and task, $F(1, 64) = .12$, $p = .727$, $\eta_p^2 = .002$. The main effect of inducer type was also non-significant, $F(1, 64) = .59$, $p = .444$, $\eta_p^2 = .009$. For C, there was no main effect of inducer size, $F(1, 64) = 1.69$, $p = .199$, $\eta_p^2 = .026$, nor a main effect of task, $F(1, 64) = .15$, $p = .697$, $\eta_p^2 = .002$. Further, there was no interaction between inducer size and task, $F(1, 64) = .02$, $p = .897$, $\eta_p^2 < .001$. There was no main effect of inducer type on C, $F(1, 64) = 1.55$, $p = .217$, $\eta_p^2 = .024$, however, there was an interaction between inducer type and task, $F(1, 64) = 5.19$, $p = .026$, $\eta_p^2 = .075$. All other effects were non-significant. Therefore, consistent with our accuracy analyses, this analysis suggests that changes in inducer size have a similar effect on perceptual sensitivity for both spatial and temporal acuity, while having minimal effects on response criterion.

Checking the Assumption of Normality

Finally, it is important to note that across both experiments, accuracy data in the spatial and temporal gap tasks often violated the assumption of normality. This was the case even though no univariate outliers were detected in the data. Although ANOVAs are relatively robust to normality violations (Glass, Peckham, & Sanders, 1972), to check whether this unduly influenced our results, we also ran non-parametric analyses to confirm the effect of attention scaling on visual perception. As no non-parametric analysis for a 2x2 repeated measures ANOVA exists, we ran four non-parametric t-tests. For Experiment 1, a Wilcoxon signed ranks test revealed a significant effect of motion inducer size on accuracy in the spatial gap task, $Z = -2.55$, $p = .011$, and a non-significant effect on accuracy in the temporal gap task, $Z = -1.78$, $p = .075$. For Experiment 2, the effect of Glass inducer size on performance was non-significant

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for the spatial gap task, $Z = -1.90$, $p = .058$, and the temporal acuity task, $Z = -1.55$, $p = .121$. However, non-parametric tests typically have lower power (e.g. Nahm, 2016). Therefore, to increase statistical power, we analysed the data from both experiments to test the effect of inducer size on both spatial and temporal acuity generally (i.e. the type of inducer used to manipulate attention was not included in this model).⁶ Overall, this non-parametric analysis revealed an effect of inducer size on both spatial acuity, $Z = -3.16$, $p = .002$, and temporal acuity, $Z = -2.38$, $p = .017$. Thus, taken together, this is broadly consistent with the finding that inducer size influences both spatial and temporal acuity.⁷

General Discussion

The ability to narrow or broaden spatial attention resources is important for processing in challenging visual tasks. The zoom lens model assumes that attention scaling influences all aspects of visual perception (Eriksen & James, 1986; Eriksen & Yeh, 1985), however, recent empirical evidence suggests that narrowing attention might have discrepant effects on spatial acuity versus temporal acuity (Goodhew et al., 2017, 2016). Nonetheless, this recent model of selective spatial enhancement has only been tested using different sized unfilled shapes to manipulate attention. These unfilled shapes may have caused participants to distribute attention as an annulus, rather than scale their attention across the entire intended manipulated region. To address this, we used a new method to manipulate attention scale, which encouraged participants to spread attention, rather than shape it as an annulus. Specifically, in Experiment 1 we used global motion stimuli of different sizes, and in Experiment 2, we used Glass pattern stimuli. Unlike the shape inducer, these two types of inducer stimuli encouraged individuals to spread attention across the entire manipulated region to pool local level visual signals. Critically, across both experiments, we found that maintaining a narrow attention scale improved both spatial and

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temporal acuity. These tasks likely required parvocellular and magnocellular input respectively. Thus, taken together, this contests the recently proposed selective spatial enhancement model of attention.

The finding that attentional scaling influenced both spatial and temporal acuity is consistent with the zoom lens model of attention scaling, as well as early work showing attention scaling to improve temporal resolution in a visual search task (Eriksen & James, 1986; Poggel et al., 2006). In Poggel et al. (2006), temporal resolution was improved under narrow attention in a visual search task for a flickering target. Further, similar to the current study, in Poggel et al. (2006), it is likely that participants were required to spread their attention evenly across all possible target locations. Therefore, it appears likely that narrowed scale of attention can improve temporal acuity, potentially related to magnocellular mediated processing.

Nonetheless, here, it is important to note that the results of the current study are unable to be directly reconciled with the findings of studies exploring the effect of *exogenous* attentional scaling on spatial and temporal perception (Mounts & Edwards, 2017). In Mounts and Edwards (2017), the scale of attention was manipulated exogenously using a cueing task. Specifically, different sized shape segments were used as peripheral cues to automatically capture and alter attention scale. Following the cue, spatial and temporal acuity targets were presented alongside the shape segments. Although shape segments may be thought to encourage an annulus distribution of attention, unlike Goodhew et al. (2016), targets were presented adjacently to inducer shape segments, meaning that the distance between the inducer and target did not vary with inducer size. Thus, it is unlikely that in Mounts and Edwards (2017), attention was distributed as an annulus, even though unfilled shape segments were used to manipulate attention. Critically, although the small cued condition led to improved spatial acuity compared to the large

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cued condition, the opposite pattern of results was obtained for temporal acuity. That is, temporal acuity was improved for the large cue condition compared to the small cue condition. This suggests that exogenous attention scaling may have differential effects on temporal acuity compared to endogenous attentional scaling. However, given that Mounts and Edwards (2017) cueing procedure required participants to both shift and scale attention to the target location, as well as used a predictive cue, future work should aim to systematically study the effects of endogenous and exogenous attention scaling on temporal acuity, using a single experimental paradigm, which only requires attentional scaling.

Critically, the results of the current study directly call into question the use of unfilled shapes to manipulate the scale of attention such as those used in Goodhew et al. (2017, 2016). Based on the current study, it appears that the shape inducer used in Goodhew et al. (2017, 2016) encouraged an annulus distribution of attention. This is vitally important to highlight, as much research testing attentional scaling and visual perception has used unfilled shapes to alter the scale of attention (e.g. Castiello & Umiltà 1990; Greenwood & Parasuraman, 1999; Yeshurun & Carrasco, 2008). Instead, it is likely that unfilled shapes provide spatial structure to a visual scene, which can alter the region over which attention is deployed (e.g. Egly & Homa, 1984; Jefferies and Di Lollo, 2015; Lawrence et al., 2018; Taylor et al., 2015). For example, Jefferies and Di Lollo (2015) tested the effect of adding spatial structure to a visual attention display using placeholder stimuli. Participants were required to identify two peripheral letters shown in a rapid serial visual presentation, while a stream of distractor digits was presented centrally. In one condition, placeholder boxes were presented alongside the stimuli, which indicated potential locations the critical target could appear. These placeholders were arranged as an annulus, providing the object contours of an annulus to the visual display. In the other condition, no

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placeholders were present. Crucially, the addition of placeholder stimuli led to higher levels of accuracy in the peripheral letter rapid serial visual presentation task. This suggests that the spatial structure afforded by the placeholders allowed participants to distribute attention as an annulus, reducing the amount of distraction (i.e. attention given) to the central letter display. Therefore, when manipulating attention, future research should move to use methods similar to those adopted in the current study. This will ensure valid conclusions regarding spatial attention scaling are made.

Finally, although the current work suggests that sustaining a narrow scale of attention improves all aspects of visual processing, there are many cases in which a broad scale of attention might be most beneficial. For instance, Chong and Treisman (2005) tested the effect of different types of visual search arrays on the processing of average size. Participants completed both pop-out and non-pop out visual searches for broken and unbroken circles. The authors hypothesised that a pop-out visual search would lead participants to adopt a relatively broader scale of attention, while the non-pop-out search would lead participants to adopt a relatively narrower attention scale. Overall, the authors observed that when conducting a pop-out visual search, participants found it easier to make judgements of the mean size of the search array compared to when they conducted a search for a target that did not pop-out in the search array. Likewise, it has been found that narrowing attention can impair performance on texture grouping tasks (Carrasco & Yeshurun, 1998). Critically, both of these studies require participants to pool local visual signals for coherent perception. Given the likelihood that both ventral and dorsal visual processing mediate the pooling of local level visual information (such as when processing global motion and Glass stimuli, e.g. Edwards & Badcock, 1994; Wilson & Wilkinson, 1998), one viable area for future work is to directly explore the effects of attentional scaling on ventral

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and dorsal mediated visual perception. In particular, it would be interesting to see whether the effect of scaling on these higher levels of visual perception is similar for both channels of visual processing. This could be achieved using global motion and Glass pattern inducers to both manipulate attention and measure the effects of scaling on inferred ventral and dorsal mediated processes.

To conclude, the critical finding of the current study was that attentional scaling influenced performance in both a spatial acuity and a temporal acuity task. This favours the zoom lens model of attention scaling, which argues that narrowing attention improves all aspects of visual processing (Eriksen & James, 1986). Critically, we have demonstrated that the method used to manipulate attention scale qualitatively influences the relationship between spatial attention and visual perception, such that it appears that the widely-used method of relying on unfilled shapes to manipulate attentional scale likely results in changes in attentional shape, rather than scale. As such, we encourage future researchers to carefully consider the method of manipulation they choose to alter spatial attention scale before testing the effects of attention on vision.

Notes

1. One participant reported being colour blind, but this would not alter performance in the spatial acuity task, and their vision was deemed normal. One participant chose not to wear glasses but performed above chance in all conditions, so was deemed their vision was still within the normal range.
2. There was a slight difference in the inter-trial interval for small versus large inducer block, where the inter-trial interval was approximately 300ms longer in the large inducer blocks in Experiment 1. However, we deemed this unlikely to have influenced the obtained pattern of results. This is because most likely effect that a longer inter-trial interval would have would be to cause the effect of the large inducer to dissipate, leading to a constriction of attention to a more focal region. This would make it less likely to observe an effect of inducer size on spatial acuity, and the results did not indicate this. Nonetheless, this error was rectified in Experiment 2.
3. In Experiment 1, two sets of participant's acuity data were recoded due to reverse responding. In Experiment 2, one data set was recoded. Reverse responding was determined by checking whether in either the spatial or the temporal task, a participant scored below 50% accuracy in both the small and large inducer conditions.
4. In Experiment 1 and Experiment 2, due to a coding error, threshold estimates recorded in the study were taken from 2nd last trial of an experimental block.
5. We thank an anonymous reviewer for pointing out the non-linear relationship between accuracy and sensitivity. It is important to note that in both Experiment 1 and Experiment 2, a large number of data points had hit rates of 100%, and false alarm rates of 0%. In Experiment 2, for target present trials 47.9% of data points had a hit rate of 100%. For

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target absent trials, 27.9% of data points had a false alarm rate of 0%. Further, in Experiment 1, for target present trials, 40.3% of data points had a hit rate of 100%. For target absent trials, 24.2% of the data points had a false alarm rate of 0. Therefore, across both experiments, a large proportion of data suggested ceiling levels of performance and was being corrected.

6. Some individuals participated in both Experiment 1 and Experiment 2 of the current study. However, participants never completed both experiments within the same testing session. Before running the combined non-parametric analyses, we first conducted an ANOVA with inducer size, and gap task as within-subject factors, and inducer type as a between-subject factor. This analysis revealed that the type of inducer (motion versus Glass), did not influence the overall relationship between inducer size and accuracy, $F(1, 64) = .42, p = .522, \eta_p^2 = .006$.
7. The assumption of normality was also violated across both experiments for threshold, and response time data. Non-parametric analysis of this data yielded largely similar results to the parametric analysis. As such, parametric analyses are reported in the manuscript.

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