Running Head: Scope of attention and temporal resolution

Word count: 2986

Broad scope of attention results in better temporal resolution: Evidence from a temporal order
judgment study

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Abstract

The nature of spatiotemporal interactions in visual perception due to modulations of attention is still not well understood. Transient shifts of attention have been shown to induce a trade-off in spatiotemporal acuities at the cued location. Attention also can be varied in terms of scope and the evidence for the effects of scope on the spatiotemporal resolution for coupling or trade-offs have been equivocal. We predicted that scaling or changing the scope of attention would rather result in a spatiotemporal trade-off based on the complementary spatial and temporal frequency properties of the magnocellular and parvocellular channels. We manipulated the scope of attention by asking participants to perform a global or local target detection task with hierarchical stimuli. In addition, participants performed a temporal order judgment task with two discs presented alongside the hierarchical stimuli. We found higher temporal sensitivity with broad scope of attention or global processing compared to narrow scope of attention or local processing. The results provide evidence for a spatiotemporal processing trade-off when attention is scaled spatially. This result throws doubt on a general coupling or resource metaphor explanation irrespective of the spatial or temporal nature of the tasks. The results indicate the further need for carefully investigating the spatial and temporal properties of attention and its effect on spatiotemporal processing at different scales.

Keywords: scope of attention, scaling, temporal resolution, processing trade-off, global processing, local processing, temporal order judgment

Introduction

Modulating spatial attention influences spatial and temporal sensitivities of our visual perception (Carrasco, 2011; Correa et al., 2006; Lawrence, 2020a; Sharp et al., 2018; Spencer & Parise, 2010). Transient shifts of attention enhance spatial resolution at the attended location (Yeshurun & Carrasco, 1999; Carrasco, 2011), even if it impairs performance in a texture segregation task presented at foveal location (Yeshurun & Carrasco, 1998; Carrasco, 2011). Sustained attention, on the other hand, has been shown to be adaptive and compliant with task demands in modulating the spatial resolution with covert shifts of attention in space with performance improvements at all eccentricities using a similar task as above (Yeshurun et al., 2008; Carrasco, 2011).

Spatial attention can also be scaled (Eriksen & Yeh, 1985). Broadening the scope of attention has been shown to increase sensitivity to lower spatial frequencies and narrowing the scope to increase sensitivity to higher spatial frequencies (Shulman & Wilson, 1987; Hughes et al., 1996). Employing a broader compared to narrow scope of attention results in a poorer spatial resolution (Merigan & Maunsell, 1993; Hughes et al., 1996; Balz & Hock, 1997; Carrasco, 2011; Lawrence et al., 2020b). However, there is no clear consensus on whether spatial scope of attention, while it modulates spatial resolution, influences temporal resolution (Lawrence et al., 2020b).

There are predominantly two hypotheses about the relationship between spatial and temporal resolutions: *coupling* and *trade-off*. The *coupling* hypothesis entails that as the attentional scope is narrowed, there is an enhancement in both spatial and temporal resolutions of the visual system which, in essence, is a generalization of zoom-lens account (Eriksen & St. James, 1986; Lawrence et al., 2020a; 2020b). In contrast, the *trade-off*

hypothesis entails that with narrow scope, spatial resolution is enhanced, accompanied by a subsequent impairment in temporal resolution.

Evidence for the trade-off hypothesis comes from the two-channel theories in visual perception in which the two channels exhibit an inherent spatiotemporal trade-off (Kulikowski & Tolhurst, 1973, Tolhurst, 1975; Merigan & Maunsell, 1993; Yeshurun & Levy, 2003). The transient or the magnocellular channel is more sensitive in processing low spatial frequency information but high temporal-frequency information, vice-versa for the sustained or the parvocellular channel. In terms of spatial attention, Yeshurun & Levy (2003) argue that transient attention degrades temporal resolution while improving the spatial resolution at the exogenously cued location, implying a trade-off.

To explain the presence of the trade-off, Yeshurun & Levy (2003) emphasize the neurophysiological evidence for processing trade-offs in magnocellular (M) and parvocellular (P) neurons. They argue that an attentional mechanism that could activate the P-cells relatively more than the M-cells can explain the finding of enhanced spatial acuities at the attended location while also explaining the degraded temporal acuities (Yeshurun & Levy, 2003; Yeshurun, 2004). In contrast, Attentional Attraction Field (AAF) account attempts to explain the enhanced spatial resolution due to the higher sampling density caused by the hierarchically converging receptive fields due to focused attention. The impaired temporal resolution is due to the increased variability of the population activity whose average response is sustained longer. This degrades the precision in time (Baruch & Yeshurun, 2014).

Some studies have contested the evidence for spatiotemporal trade-offs and argue for spatiotemporal coupling (Hein et al., 2006, Poggel et al., 2006). Poggel et al. (2006) employed a DPR (double pulse resolution) paradigm with dots arranged in a circular grid with varying eccentricity from the centre. Results suggest that the smaller the area over which

the attention is distributed, the better is the temporal sensitivity. They argue that sustained attention might have different dynamics than transient attention, resulting in a spatiotemporal coupling. However, the dependent variable is not purely a measurement of just temporal resolution but of both spatial and temporal sensitivities. The thresholds were measured depending on the reports of 'where' they saw a double pulse and not 'whether they saw a double pulse.'

Studies that have manipulated scope of attention or scaling have produced mixed results (Goodhew et al., 2016; 2017; Lawrence et al., 2020a; 2020b; Mounts & Edwards, 2017). There is evidence for a trade-off in spatiotemporal acuities with spatial scope manipulated using cue size (Mounts & Edwards, 2017). With an increase in cue size, the accuracy in the spatial acuity task was reduced, but the accuracy in the temporal acuity task was enhanced. Goodhew et al. (2016, 2017) manipulated the scope of attention using different-sized shapes as scope inducers. The inducer trials (80%) are interspersed with the spatial/temporal acuity task trials (20%). They showed that narrowing the scope of attention improved spatial task performance, but the temporal task performance did not significantly change. It should be noted here that the task itself does not necessitate that one holds the induced scope of attention while it is being performed. The differences were explained using the notions of exogenous and endogenous attention (Mounts & Edwards, 2017; Lawrence et al., 2020b). More recently, Lawrence et al. (2020a) manipulated scaling in which information has to be pooled across the whole stimulus and showed that both spatial and temporal acuity task performance was better with a narrow attentional scale.

Given the lack of clarity on the link between scope of attention and temporal processing, the current study manipulated scope of attention to investigate its effect on temporal resolution. We hypothesized a spatiotemporal trade-off associated with changes in

the spatial scope of attention given the evidence for such trade-offs in the literature. Given the evidence for two channels that differ in terms of spatiotemporal properties (Kulikowski & Tolhurst, 1973; Tolhurst, 1975; Merigan & Maunsell, 1993) or cuing mechanisms that exhibit a spatiotemporal trade-off (Yeshurun, 2004; Baruch & Yeshurun, 2014) and also the evidence linking scope of attention to spatial resolution (Merigan & Maunsell, 1993; Balz & Hock, 1997; Carrasco, 2011; Lawrence et al., 2020b), we predicted that broadening the scope of attention would impair temporal resolution and vice versa.

We manipulated the scope of attention using hierarchical stimuli (Robertson et al., 1993). Global processing is associated with broad scope of attention, and local processing is associated with narrow scope of attention. While participants performed a task associated with a broader or narrower scope, they were also asked to perform a temporal order judgement (TOJ) task, that is, to report the order of two discs that appeared close in time with a variable stimulus onset asynchrony (SOA). Unlike many earlier studies (Goodhew et al., 2016; 2017; Lawrence et al., 2020a), stimuli for the TOJ task were shown along with the primary attentional scope stimulus and both tasks have to be performed in the same trial. We use SOA as a parametric variable rather than a categorical variable (Goodhew et al., 2016; Yeshurun & Levy, 2003).

We fit a psychometric function for the TOJ judgments in both attentional scope conditions and use the slope (b) parameter of the psychometric (logistic) function as a measure of temporal resolution. Given that the TOJ task's response is affected by various response errors (García-Pérez & Alcalá-Quintana, 2012; 2015), there is a need to disambiguate the source of the results. We also fit our data to the Independent Channel (IC) model, initially developed for cross-modal TOJ tasks. According to the model, the two modality stimuli are processed by independent channels with different timing properties to

furnish a 'perceived onset time' for each from a particular distribution. There is an internal 'decision rule' that the system applies on these perceived onsets to generate a response from the two choices in a TOJ task, besides allowing for different sources of response errors. The model has been simplified to accommodate the same modality TOJ tasks as well (García-Pérez & Alcalá-Quintana, 2015). With the IC model (García-Pérez & Alcalá-Quintana, 2012; 2015), the parameter of interest is δ , the decisional or the resolution parameter that limits with what precision one can differentiate the perceived onsets. We predicted that as the scope scales broader in space, the 'delta' value decreases, i.e., the temporal resolution gets finer.

Methods

Participants

Forty volunteers with a normal or corrected-to-normal vision from Allahabad University participated in the experiment. Participants with below 80% accuracy in the target identification task and goodness of fit statistic (R^2 less than 0.8) were excluded. As a result, data from nine participants was excluded leaving 31 participants (11 females, Age range = 20 to 30 years) in the study. The sample size calculations were done a priori using G*Power software for a one-tailed matched paired t-test with power = 0.85, alpha = 0.05, medium effect size of $d_z = 0.5$, giving desired $N = 31$. The study was conducted with approval from the Ethics Committee at University of Allahabad. Participants were compensated for their time.

Stimulus and Apparatus

The stimuli were presented using E-Prime 2.0 developed by Psychology Software Tools.

Hierarchical letters were used as stimuli to manipulate the scope of attention. In addition, two circular discs vertically spaced and equidistant from the centre flashed one after the other.

The targets were always the letters H or S in both the global and local tasks (figure 1). The letter at the other level was one from E, Y, inverted E, and inverted Y. The size of the hierarchical letter (global letter) was $14.2^\circ \times 10.54^\circ$, and that of the local letter was $1.76^\circ \times 0.79^\circ$. The diameter of the discs was 0.79° . The distance of each disc from the centre of the hierarchical letter was 3.125° . Participants sat approximately at 65cm from a 17" CRT monitor with a resolution of 1024x768 and a refresh rate of 100Hz. The experiment lasted approximately 40 minutes.

Figure 1: Stimuli used in the experiment. The first two rows were presented in the global block. The last two rows were presented in the local block. The target letters of interest were S/H in both the blocks.

Procedure

The experimental trials were blocked into either a global or a local target identification task. In each block, each trial started with an instruction displaying the level of the hierarchical stimulus to be identified. Participants began each trial by pressing the space bar. The hierarchical letter appeared 200ms after the keypress, followed by the presentation of two discs one after another, which were presented alongside the hierarchical letter. The first disc appeared 50 ms after the presentation of the hierarchical letter. The discs were presented for 10ms each. The SOA between the discs was varied (10ms, 30ms, 50ms, 70ms, 90ms and 110ms). The hierarchical letter was removed 50ms after the disappearance of the second disc and replaced with a blank display. At the end of each trial, participants were first asked to report the temporal order of the discs by pressing the UP or DOWN arrow on the keyboard if they saw the upper disc or lower disc flash first, respectively. Then they were asked to report the target by pressing H or S on the keyboard for the same. The experiment did not proceed to the next trial until the responses were made. Participants were not given any feedback on their performance. Participants did a practice session of 24 trials so that they become familiar with the tasks before the main experiment.

There were 12 different SOAs between the two discs (-110ms, -90ms, -70ms, -50ms, -30ms, -10ms, 10ms, 30ms, 50ms, 70ms, 90ms, 110ms; positive SOA when the upper disc flashes first and negative SOA when the lower disc flashes first). For each stimulus, the discs appeared at each SOA 6 times, making the total number of trials for each level task sum to 288 (4x12x6). The total number of trials, therefore, for global and local level tasks sum up to 576 (288x2). The global/local blocks were further divided into two blocks each, presented in

an ABAB fashion to minimize order effects. The order of the blocks was counterbalanced among the participants.

Figure 2: The figure depicts the procedure of the experiment. Participants began each trial with a keypress. A hierarchical stimulus appeared first for 50ms. This was followed by the onset of the two discs (10ms presentation time for each) with a variable SOA between them. The discs were presented above and below the centre of the stimulus. Participants were asked to report which disc appeared first and the target identity (at local/global level in different blocks). See text for more.

Results

A Wilcoxon Signed Rank test was done for the accuracies for target identification in global and local conditions (Shapiro-Wilk test for normality: $W = 0.906$, $p = 0.01$). Accuracies for the local block ($M = 96.05\%$, $SD = 3.32\%$) were significantly higher ($W = 75$, $p = 0.004$, matched rank biserial correlation = 0.631) than for the global block ($M = 94.20\%$, $SD = 4.77\%$).

For each participant, trials in which they misidentified the global or local target were eliminated from further analysis. We fitted the data from the TOJ task in the global and local scope conditions for each participant with a general logistic function: $y = 1/(1 + e^{-b(x-a)})$, in which a is the intercept/point of subjective equality (PSE) and b is the slope using MATLAB's curve-fitting toolbox. We used slope parameter b as the temporal sensitivity measure. On the x-axis, SOA varied from -110ms to 110ms in steps of 20ms. The y-axis was the proportion of responses (0 to 1) where participants had pressed the UP arrow (further referred to as proportion-up responses). R^2 values, after exclusion of participants, were between 0.83 and 0.99. A sample pair of psychometric curves for global and local conditions from a participant is shown in Figure 3.

The normality assumption was violated (Shapiro-Wilk test: $W = 0.791, p < 0.001$) for the slope values. The slope in the global condition ($M = 0.089, SD = 0.081$) was significantly higher than that in the local condition ($M = 0.066, SD = 0.049$) as per the one-sided Wilcoxon Signed Rank test ($W = 349, p = 0.024$, matched rank biserial correlation = 0.407).

Figure 3: Psychometric functions fit for data from global (in blue) and local (in red) scope conditions for a single participant, showing higher slope in global condition than in local.

To check whether the accuracy difference in the target identification is associated with the slope difference in the TOJ task, we performed a non-parametric correlation between the accuracy and slope differences between the global and local conditions across participants.

The correlation was not significant, $r_t = 0.178$, $p = 0.163$.

A paired t-test for PSEs revealed that PSE values are significantly different in the global scope condition ($M = -8.068\text{ms}$, $SD = 19.86\text{ms}$) compared to the local scope condition ($M = -14.154\text{ms}$, $SD = 18.52\text{ms}$), $t(30) = 2.784$, $p = 0.009$ (two-tailed), $d = 0.5$. The more negative PSE values in the local condition imply a larger bias towards perceiving the upper disc as appearing earlier in the local condition compared to the global condition.

Figure 4: (a) Means of slope parameters for global and local conditions as fit by the psychometric function. Higher the slope, better the temporal resolution. (b) Means of delta parameters (as obtained from the IC model) for global and local conditions. Lower the delta, finer the temporal resolution.

We also fit the TOJ task data using the Independent Channels (IC) model (García-Pérez & Alcalá-Quintana, 2012; 2015) for each participant using the MATLAB code published by the authors (Alcalá-Quintana & García-Pérez, 2013). The fit consisted of five parameters including δ , λ , ξ , and the two ε s. Since the two stimuli belong to the same modality, $\tau = 0$, and there is only one λ parameter (García-Pérez & Alcalá-Quintana, 2015). G^2 statistic was significant for seven participants and thus were eliminated from further analysis. A one-sided paired t-test was performed on the δ parameter, which is also called the ‘resolution parameter’ according to the model. As expected, the resolution parameter was significantly smaller (hence finer) in the global condition ($M = 15.72\text{ms}$, $SD = 14.70\text{ms}$) when compared to the local condition ($M = 25.99\text{ms}$, $SD = 21.67\text{ms}$), $t(23) = -2.844$, $p = 0.005$, $d = -0.58$. Additionally, no other parameter was significantly different in the two conditions ($ps > 0.5$).

A Wilcoxon Signed Rank test on accuracies in the target identification task revealed a significant difference with accuracies in local condition ($M = 95.8\%$, $SD = 3.2\%$) larger ($W = 53$, $p = 0.018$, matched rank biserial correlation = 0.581) than accuracies in global condition ($M = 94\%$, $SD = 5.1\%$). We also performed a non-parametric correlation between delta-difference and accuracy difference across participants. Once again, the correlation was not significant $r_t = 0.044$, $p = 0.766$ indicating that the accuracy difference is not linked to the difference in δ values between the global and local conditions.

Discussion

Changing the spatial scope of attention modulates the temporal resolution of the visual system. More specifically, the higher slope for the temporal order judgment (TOJ) task in the global condition suggests that broadening the spatial scope is associated with improving

temporal resolution. Our data fit with the IC model further strengthens the claim that the difference is indeed in the temporal resolution between the two scope conditions, with only the decisional parameter (δ) being significantly different between the two scope conditions.

Our results are consistent with the spatiotemporal trade-off hypothesis. It predicts that when the system is modulated to process information with a high spatial resolution (by narrowing the scope of attention), it results in degradation of the temporal resolution and vice versa. Such a trade-off account is evident in studies that show an enhanced spatial resolution at the attended location but an impaired temporal resolution (Yeshurun & Levy, 2003; Mounts and Edwards, 2017; Hein et al., 2006; Lawrence et al., 2020b).

Support for a trade-off is consistent with the functional divergence in processing spatiotemporal information by the two visual pathways (Kulikowski & Tolhurst, 1973, Tolhurst, 1975; Merigan & Maunsell, 1993; Yeshurun & Levy, 2003). The p-pathway is more sensitive to high spatial frequencies and low temporal frequencies compared to the m-pathway and the reverse for low spatial frequencies and high temporal frequencies (Kulikowski & Tolhurst, 1973, Tolhurst, 1975; Merigan & Maunsell, 1993). A possible mechanism to explain such a trade-off in attention studies was proposed by Yeshurun & Levy (2003). According to them, attentional shifts in space might facilitate parvocellular activation relatively more, resulting in a sharper spatial resolution at the attended location while simultaneously impairing magnocellular activation resulting in a poorer temporal resolution. Similar changes could underlie changes due to attentional scope resulting in worse spatial resolution and better temporal resolution with a broad scope of attention.

The results from the current study are not consistent with general arguments based on cognitive resources (Eriksen & James, 1986). According to this idea, concentration of

resources with a narrow scope would result in better processing, and more diffused resources with a broad scope would result in poor processing irrespective of the spatial or temporal nature of the task. Our results with better temporal sensitivity with a broad scope of attention indicate that it may not always be the case.

Some studies have argued against a trade-off between spatial and temporal acuity as a function of attentional scaling (Poggel et al., 2006; Goodhew et al., 2016; Lawrence et al., 2020a). Lawrence et al. (2020a) used large- or small-scale aperture motion stimuli as their primary attentional scale task. Spatial and temporal acuities measured using a spatial and temporal gap task were better with the large aperture than the small aperture motion task condition. It is to be noted that our manipulations of spatial scale and the primary attentional task is different compared to their study. In the Lawrence et al. (2020a) study, the attentional task itself is a temporal task that would have needed spatiotemporal processing and the involvement of the magnocellular or the dorsal pathway. However, our primary task was a spatial target identification task that would predominantly need the parvocellular or the ventral pathway. Our primary attentional task involved a hierarchical level difference in addition to the difference in the size of the spatial scale. In addition, while the attentional scale was blocked in both studies, ours involved simultaneously doing a global or local task and the ToJ task in all the trials. The Lawrence et al. (2020a) study had blocks where the motion task was performed in 80% of the trials and the gap task in 20% of the trials.

The influence of spatial scope of attention on temporal processing may partially depend on the nature of the primary task associated with changes in attentional scope (Lawrence et al., 2020b) with coupling when the primary attentional task involves both spatial and temporal processing and trade-offs when the primary attentional task involves predominantly spatial or temporal processing. For example, endogenous vs. exogenous

manipulations of attentional scope could influence spatial and temporal processing differently (Lawrence et al., 2020b). Further studies would be needed to understand the changes in processing due to the specific attentional scope manipulation and the spatiotemporal requirements of the tasks involved.

While there was an accuracy difference between global and local target identification in our task, the difference in accuracy was not linked to the difference in slope between the scope conditions, as indicated by the non-significant correlations. In addition, the accuracies for both the conditions were close to the ceiling effect. Further, arguments based on attentional resources would predict that more resources for the ToJ task in the local condition given the slightly better accuracy in that condition and hence, temporal resolution should be better in the local condition.

The results from the present study are also consistent with other studies that have manipulated the scope of attention and measured different aspects of time perception (Singh & Srinivasan, in preparation). Participants identified a particular target at the global or local level and in addition, judged the duration of the hierarchical stimulus presentation. The linear function fit for the perceived duration of the global targets showed a higher slope than that of the local targets indicating better temporal sensitivity with global processing (Singh & Srinivasan, in preparation).

Previous studies have shown that temporal resolution is linked to WM capacity and intelligence (Troche & Rammsayer, 2009). The influence of scope of attention on temporal resolution is consistent with further downstream effects of scope of attention on other cognitive processes (Srinivasan et al., 2013).

Conclusion

We have shown better temporal resolution associated with broader scope of attention, indicating potential trade-offs in spatiotemporal processing. The results could be explained by the complementary spatiotemporal properties of the magnocellular and parvocellular channels and the relative activation of the two as a function of attention. The results are in contrast with the spatiotemporal coupling hypothesis and the general attentional resource metaphor used in relation to the scope of attention. Further studies would be needed to fully understand the effects of attentional scope on spatiotemporal processing.

Author Contributions

NS and RM conceptualized the study. RM wrote the programs, collected data and analyzed the data. RM and NS interpreted the results and wrote the manuscript.

Conflict of Interest Statement

The authors report no conflict of interest.

Open Practices Statement

The data and materials for the study is available at <https://osf.io/42aue/>.

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