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RESEARCH ARTICLE

Spatial and temporal acuity of visual perception can be enhanced selectively by attentional set

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Abstract The aim of this research was to study the relationship between perceptual judgments about space and time. If spatial and temporal judgments were dissociable, they should be modulated selectively by attention. We compared the effect of the attentional set upon fine-grained spatial versus temporal discrimination of visual perception in two experiments. Using identical sensory stimulation, we measured perceptual judgments on either the size of a small spatial gap or the duration of a brief temporal gap. The attentional set was manipulated by cuing the task that was most likely to be performed. In one experiment, a neutral cue was also used, to measure relative benefits and costs of spatial and temporal task sets. If the attentional set could be directed selectively to spatial and temporal task-relevant dimensions, performance on both spatial and temporal acuity tasks should be specifically modulated by task cuing. The results showed that the attentional set enhanced the speed and accuracy of perceptual judgments similarly on both spatial and temporal tasks. Moreover, accuracy in one task was selectively enhanced by attending to that task while remaining unaffected by attending to the alternative task. This finding suggests multiple mechanisms, by which visual processing of spatial and temporal features can be selectively prepared without interfering with one another.

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Introduction

In daily situations, temporal perception is often influenced by our subjective state. Focusing on the passage of time (e.g. while waiting or bored) tends to prolong our perception of time, whereas focusing on other aspects of events (e.g. while busy or distracted) tends to shorten it (Fraisse 1984). This phenomenon has been investigated by comparing conditions of focused versus divided attention within dual-task contexts, in which a non-temporal task is performed concurrently with a temporal discrimination task. Temporal discrimination tasks measure the ability to perceive temporal features accurately, such as stimulus duration. The typical result shows that judgments about duration are lengthened or shortened depending on whether attention is focused on the temporal or non-temporal task, respectively (e.g. Grondin and Macar 1992; Brown 1997, 2006; Boltz 1998; Zakay 1998; Coull et al. 2004).

Surprisingly, the competing non-temporal task in dual-task contexts has rarely involved spatial discrimination (but see Halbig et al. 1998). Research comparing space and time is important because these two dimensions impose a referential frame for perception and action. Moreover, both dimensions are closely interrelated, as suggested by the *tau* effect (i.e. influence of the temporal context over spatial judgments) and the *kappa* effect (influence of the spatial context over duration judgments; reviewed by Jones and Huang 1982). For example, studies combining spatial and temporal discrimination tasks have found that judgments of large-size stimuli are biased to long-duration estimations. This bias was found for judgments involving both prospective *perceptual* estimations (Thomas and Cantor 1975) and retrospective estimations from *memory* (Sarrazin et al. 2004; Casasanto and Boroditsky 2008). These results raise the interesting possibility that representations of spatial and temporal features may be co-dependent.

In contrast, another study found a double dissociation between the maintenance of spatial and temporal features in working memory (Halbig et al. 1998). Specifically, performance in a spatial working-memory task was selectively impaired by concurrent spatial but not temporal tasks; and performance in a temporal working-memory task was impaired by temporal but not spatial tasks. This finding leads to an alternative view: spatial and temporal representations are at least partly independent, and can be maintained and manipulated separately. To test and extend this hypothesis to the perceptual domain, we investigated whether it was possible to enhance selectively spatial versus temporal acuity of visual perception by spatial versus temporal task sets.

The task was to judge either the size (spatial interval) or the duration (temporal interval) of a stimulus containing a gap, which had both spatial and temporal extents. The attentional set was manipulated by informing participants about which task they would most probably be asked to perform. Specifically, symbolic cues indicated the target dimension to which participants were to attend, thereby inducing a preparatory set for a spatial or temporal task. If spatial and temporal judgments rely on co-dependent processes, attentional modulation of judgments along one dimension should concomitantly influence judgments along the other dimension. On the other hand, if spatial and temporal judgments can be dissociated, attentional modulation of judgments along one dimension need not influence judgments along the other dimension.

Experiment 1

Method

Participants

Ten participants took part voluntarily in Experiment 1 (aged 24–32, four males) and another 18 participated in Experiment 2 (aged 20–40, 7 males). Data from two participants in Experiment 2 were rejected due to low accuracy (below 60%) on the temporal task. The experimental methods were non-invasive and had ethical approval from the University of Oxford.

Apparatus and stimuli

The stimuli were presented on a monitor connected to a computer, which controlled the presentation of stimuli and data collection. A remote, video-based infrared eye tracker monitored eye movements. The stimuli were presented on a grey background. The fixation point was a black cross surrounded by a square (1.15° × 1.15°). The cue was either the 'S' or the "T" letters formed by colouring in red the corresponding bars of the fixation point (see Fig. 1). This letter indicated the dimension (spatial or temporal) to which the participants were to attend. The target was a square (2.35° × 2.35°) with a spatial gap on the top (0.29° and 0.58° for the small and big gaps, respectively), located at 6.75° of eccentricity either on the left or right visual field. The temporal gap consisted of the disappearance of the target for either 17 or 50 ms (short and long gaps). The response probe consisted of a foveally presented letter (similar to the cues) that indicated the task to be performed on that trial.

Procedure

The participants were seated at approximately 100 cm from the screen and were instructed to attend to the dimension indicated by the cue. They were encouraged to respond accurately and were reminded to hold their gaze at the centre throughout the experiment. Gaze position was monitored on-line to ensure that the task was performed covertly. When necessary during training, participants were provided with specific feedback to help them perform the task in the absence of any eye movements.

There were two different tasks. The spatial task demanded the estimation of the spatial gap appearing at the top of the target. Half of the participants pressed the 'a' key with the middle finger if the gap was big, and the 'z' key with the index finger if the gap was small. The temporal task demanded the estimation of the temporal gap delimited by two consecutive presentations of the same target. The

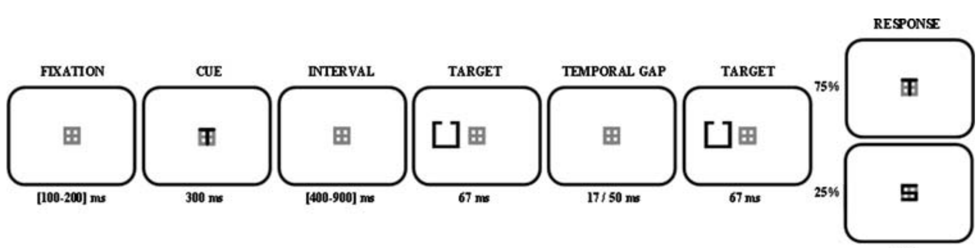

Fig. 1 Example of a trial illustrating valid (75%) and invalid (25%) conditions in Experiment 1

'k' key had to be pressed with the middle finger if the gap was long, and the 'm' key with the index finger if the gap was short. The remaining half of participants used the 'a/z' keys for the temporal task and 'k/m' keys for the spatial task. Therefore, the responses with the middle finger were always assigned to large magnitudes (big/long).

Figure 1 shows a schematic of the task. Each trial began with the appearance of a central fixation point for a random interval that ranged from 100 to 200 ms. The cue was then presented for 300 ms, followed by the fixation point for a random interval of 400–900 ms. The target appeared for 67 ms either to the left or to the right of the fixation point, disappeared for either 17 or 50 ms according to the duration of the temporal gap, and reappeared for another 67 ms at the same place. Both spatial and temporal gaps were presented on every trial. Immediately after the target, the letter indicating the task to be performed appeared and remained on the centre of the screen until the participant responded, or for a maximum duration of 4,000 ms. After the response, there was a blank display of 500 ms preceding the next trial.

Participants completed two practice blocks followed by 10 experimental blocks of 64 trials. The cue predicted the task to be performed with a probability of 0.75. Each block included 48 "valid" trials in which the task to be performed matched the cued dimension (i.e. 24 valid trials per task), and 16 "invalid" trials in which the cued and probed dimensions did not match. All possible combinations of presentations (cue, side of target appearance, size of spatial gap and duration of temporal gap) were randomly intermixed across trials.

Results and discussion

A repeated-measure analysis of variance (ANOVA) with the factors of task (spatial and temporal) and cue validity (valid and invalid) was performed on the proportion of correct responses. The analysis confirmed that performance was balanced for both tasks (main effect of task: $F < 1$). The main effect of cue validity was significant, $F(1,9) = 65.73$, $P < 0.001$, showing higher accuracy for valid as compared to invalid trials (i.e. 'validity effect'). A significant task × validity interaction, $F(1,9) = 10.89$, $P < 0.01$, revealed larger validity effects for the spatial when compared to the temporal task (see Fig. 2). Subsidiary analyses, however, showed significant validity effects for both the spatial and temporal tasks [$F(1,9) = 79.89$, $P < 0.001$ and $F(1,9) = 27.53$, $P < 0.001$, respectively].

Experiment 1 showed that either the spatial or temporal dimension could be prioritised over the other dimension to enhance processing. Thus, attention selectively modulated spatial and temporal acuities depending on which dimension, space or time, was predicted to be task relevant. But, what is the nature of these effects: are they due to independent or co-dependent mechanisms? Co-dependent mechanisms, in principle, could either be agonistic or antagonistic. Agonistic mechanisms would lead to unselective modulations. For example, if space and time shared a common representation in the brain, enhancements of spatial acuity would be indissolubly associated with enhancements of temporal acuity. The validity effects observed in Experiment 1 argued against co-dependent agonistic mechanisms, but left open two remaining possibilities. It was not possible to determine whether perceptual acuity of the spatial and temporal dimensions was controlled separately (through multiple mechanisms) or in a co-dependent antagonistic fashion, where the enhancement of acuity in one dimension occurred at the cost of acuity along the other dimension.

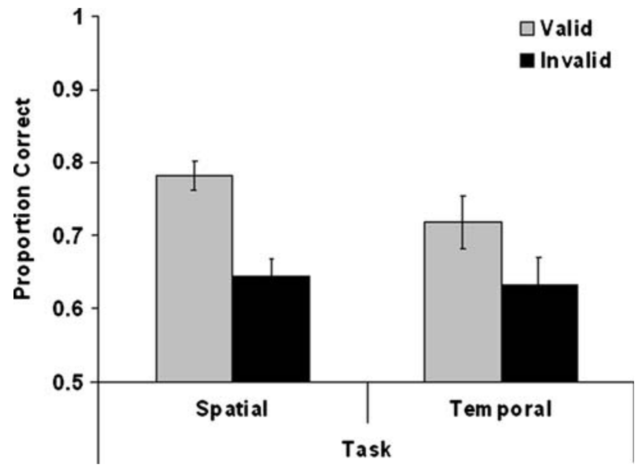

Fig. 2 Mean proportion of correct responses as a function of task (spatial and temporal) and cue validity (valid and invalid) in Experiment 1. *Error bars* represent standard errors. Valid cues improved accuracy as compared to invalid cues on both spatial and temporal discrimination tasks

By including a baseline condition, it is possible to test whether attentional enhancements on one task are accompanied by performance impairments on the alternative task, and therefore to arbitrate between the existence of co-dependent antagonistic versus independent mechanisms. Experiment 2 included a neutral condition as baseline to measure behavioural benefits and costs, to discern between these two possibilities. The existence of multiple and dissociable mechanisms would be supported by finding that performance in one task could be selectively enhanced while performance in the alternative task remains unaffected. If instead, the mechanisms are antagonistic, attentional benefits in spatial acuity would be accompanied by costs in temporal acuity and vice versa.

Experiment 2

Experiment 2 included a baseline condition to investigate whether the validity effects observed in Experiment 1 by using neutral, non-informative cues were due to behavioural benefits or costs. The symbol resulting from the combination of 'S' and 'T' letters was used as neutral cue, which predicted the subsequent task with a probability of 0.50. As is standard, benefits referred to performance improvements in the valid versus neutral condition, whereas costs referred to performance impairments in the invalid versus neutral condition.

Task difficulty was individually adjusted by a staircase procedure, to balance the accuracy of performance in both tasks and to prevent floor and ceiling effects. The size of the big spatial gap changed between blocks according to the mean accuracy. It was reduced from 0.58° to 0.43° if accuracy was above 0.85, or enlarged to 0.72° if accuracy was below 0.75. Analogously, the duration of the long temporal gap was shortened from 50 to 34 ms, or lengthened to 67 ms to maintain performance levels between 0.75 and 0.85. Task instructions emphasised making speeded responses without compromising accuracy. Reaction times (RTs) were analysed to confirm that the attentional modulations were not simply due to speed-accuracy tradeoffs.

The stimulus display and parameters were similar to Experiment 1, but included several minor changes. To reduce overall illumination and eye fatigue, the grey background was replaced by a black background, and grey and white were used for fixation and cue, respectively. The fixation point was presented for a random interval of 500–1,000 ms and the cue-target interval for 600–1,000 ms. Moreover, to illustrate the difference between the size of the gap to be discriminated in the spatial task and the difference between the duration of the gap to be discriminated in the temporal task, participants completed 1 practice block of 16 trials in which the presentation of small and big spatial gaps was alternated, followed by 16 trials in which short and long temporal gaps were also presented in alternation. They then completed 16 blocks of 20 trials, with the first one considered as practice. In total, there were 128 trials for each predictive cue (S/T), and 64 trials for the neutral cue. The validity proportion for the predictive cues was similar to Experiment 1 (0.75). Neutral cues carried no predictive value as to the relevant task (0.50). At the end of each block, the participants rested and checked their performance statistics. The size and duration of the gaps were adjusted for the following block to achieve an overall accuracy level around 0.80.

Results

Repeated-measures ANOVAs with the factors of task (spatial and temporal) and cue validity (valid, neutral and invalid) were performed separately on the proportion of correct responses and the mean RTs from correct responses. Responses given to the non-probed task (2.2%) were rejected from the analyses (e.g. a key assigned to the spatial task was pressed when the temporal task was asked). That is, the proportion of correct responses was calculated by removing responses to the wrong task. Thus, errors were confidently related to misperceptions occurring within the probed task. Responses that were slower than 2,500 ms were rejected from the RT analysis, resulting in the exclusion of 4.3% of the trials overall across all participants.

The staircase procedure kept accuracy around 0.80, and performance accuracy did not differ significantly between the spatial (0.78) and temporal (0.82) tasks ($P = 0.09$). The main effect of validity was significant, $F(2,30) = 4.18$, $P < 0.05$. Subsidiary analyses, comparing valid and invalid trials to neutral trials, revealed that validity effects were due to benefits [proportion of correct responses of 0.83 and 0.79 on valid and neutral conditions respectively; $F(1,15) = 7.4$, $P < 0.05$] rather than costs ($F < 1$). The task × validity interaction was far from significant ($F < 1$), showing similar validity effects in both tasks (see Fig. 3).

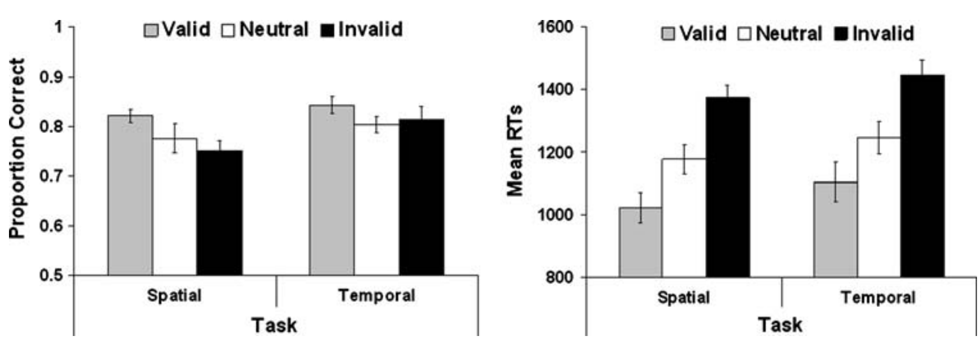

Fig. 3 Mean proportion of correct responses (*left panel*) and RTs (*right panel*) as a function of task (spatial and temporal) and cue validity (valid, neutral and invalid) in Experiment 2. *Error bars* represent standard errors. Valid cues enhanced accuracy as compared to neutral cues (attentional benefits) on both spatial and temporal tasks. In contrast, invalid cues did not impair accuracy as compared to neutral cues (attentional costs) on either task. For RTs, attentional benefits as well as costs were observed on both tasks

The RT analyses replicated the main effect of validity observed for the accuracy data, $F(2,30) = 76.86$, $P < 0.001$, which ruled out speed-accuracy tradeoffs. Subsidiary analyses revealed both significant benefits [$F(1,15) = 31.76$, $P < 0.001$] and costs [$F(1,15) = 67.04$, $P < 0.001$]. As can be appreciated in Fig. 3, the task × validity interaction was far from significant ($F < 1$).

Experiment 2 showed that the effect of attention was not dependent on the task, suggesting the operation of parallel mechanisms for enhancing the processing of spatial and temporal stimulus features. The nature of the behavioural effect was similar for both tasks. In both cases, selective improvements in accuracy occurred when the relevant task was prioritised (valid condition) as compared to the baseline, that is, when the spatial and temporal acuity tasks were equally attended (neutral condition). Benefits in accuracy were accompanied by both costs and benefits in RT, which could be due to response preparation effects, as the cue provided information regarding the response-key pair that would be most probably used.

Discussion

We explored whether directing attention to a particular task set could influence the spatial and temporal acuities of visual perception selectively. This novel approach allowed the simultaneous investigation of attentional effects on spatial and temporal discrimination tasks involving comparable perceptual stimulation.

Experiment 1 showed that attention influenced performance in both spatial and temporal discrimination tasks. Perceptual judgments were more accurate when they were applied to the cued rather than the uncued dimension of the target. Experiment 2 further revealed that attending to a stimulus dimension conferred behavioural advantages in relation to the baseline condition, in which attention was equally distributed to or arbitrarily switched between the spatial and temporal dimensions. This result was observed for accuracy and RT measures, and was not dependent on the task performed. Furthermore, enhancement of accuracy along one dimension did not cause concomitant decrements in accuracy along the other dimension.

On the basis of the pattern of results, it is not possible to determine whether they reflect primarily the operation of attentional biases that improve spatial or temporal processing according to the predictive information of the cue or the need to switch task set when the probe stimulus calls for a decision concerning the uncued dimension. The former explanation emphasises attentional benefits, and is partly supported by the finding of accuracy benefits in Experiment 2. However, it is possible that in the 'neutral' condition of this experiment participants arbitrarily committed to one set on a trial-by-trial basis. In this case, the neutral condition would have been associated with a larger number of set switches and, consequently, with poorer performance accuracy than the valid condition. However, if the requirement for switching task sets was the whole explanation, invalidity costs in accuracy might also have been expected.

Invalidity costs were observed in RTs but not in accuracy. This extra time could reflect the strategy of switching the set towards the probed task without compromising accuracy. Alternatively, they could reflect impaired temporal and spatial judgements when attention was focused on another dimension. In the temporal domain, most cognitive models propose that the attentional resources deployed to timing determine the fidelity with which time units are represented (Zakay and Block 1996; Brown 1997). Interference with timing estimates has been consistently reported when attention is directed away from time (Grondin and Macar 1992).

Regardless of the specific mechanisms supporting the effects—anticipatory attentional biases and/or set switching—they show some degree of independence between the processing of spatial and temporal aspects of events, and argue against a strict and obligatory co-dependence between temporal and spatial estimation processes (e.g. Walsh 2003). Functional segregation between the processing of timing and other stimulus features is also supported by neuroimaging research. Selective attention to temporal discrimination versus colour discrimination specifically activated the pre-supplementary motor area and the frontal operculum in the prefrontal cortex (Coull et al. 2004). Studies comparing directly spatial and temporal processing across different tasks (perceptual and motor tasks) and modalities (e.g. Schubotz and von Cramon 2001; Schubotz et al. 2003) have also found a specific involvement of the supplementary motor area and frontal operculum in temporal tasks, which suggests some degree of functional segregation for temporal processing.

To summarise, the finding that attention can affect each dimension separately is important because it supports a certain degree of specialisation and segregation between spatial and temporal processing, rather than a unitary or fully co-dependent mechanism. This finding is consistent with previous brain research, showing some functional segregation between temporal and spatial processing in different types of tasks (Schubotz and von Cramon 2001), and complementary to behavioural research suggesting the independence between spatial and temporal representations in working memory (Halbig et al. 1998). Here, we observed selective enhancements of spatial and temporal discrimination in the perceptual domain by the attentional set.

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References

Boltz MG (1998) The processing of temporal and nontemporal information in the remembering of event durations and musical structure. J Exp Psychol Hum Percept Perform 24:1087–1104

Brown SW (1997) Attentional resources in timing: interference effects in concurrent temporal and nontemporal working memory tasks. Percept Psychophys 59:1118–1140

Brown SW (2006) Timing and executive function: bidirectional interference between concurrent temporal production and randomization tasks. Mem Cognit 34:1464–1471

Casasanto D, Boroditsky L (2008) Time in the mind: using space to think about time. Cognition 106:579–593

Coull JT, Vidal F, Nazarian B, Macar F (2004) Functional anatomy of the attentional modulation of time estimation. Science 303:1506–1508

Fraisse P (1984) Perception and estimation of time. Annu Rev Psychol 35:1–37

Grondin S, Macar F (1992) Dividing attention between temporal and nontemporal tasks: a performance operating characteristic—POC—analysis. In: Macar F, Pouthas V, Friedman W (eds) Time, action, cognition: towards bridging the gap. Kluwer, Dordrecht, pp 119–128

Halbig TD, Mecklinger A, Schriefers H, Friederici AD (1998) Double dissociation of processing temporal and spatial information in working memory. Neuropsychologia 36:305–311

Jones B, Huang YL (1982) Space–time dependencies in psychological judgment of extent and duration: Algebraic model of the tau and kappa effects. Psychol Bull 91:128–142

Sarrazin JC, Giraudo MD, Pailhous J, Bootsma RJ, Giraudo MD (2004) Dynamics of balancing space and time in memory: tau and kappa effects revisited. J Exp Psychol Hum Percept Perform 30:411–430

Schubotz RI, von Cramon DY (2001) Functional organization of the lateral premotor cortex: fMRI reveals different regions activated by anticipation of object properties, location and speed. Cogn Brain Res 11:97–112

Schubotz RI, von Cramon DY, Lohmann G (2003) Auditory what, where, and when: a sensory somatotopy in lateral premotor cortex. Neuroimage 20:173–185

Thomas EAC, Cantor NE (1975) On the duality of simultaneous time and size perception. Percept Psychophys 18:44–48

Walsh V (2003) A theory of magnitude: common cortical metrics of time, space and quantity. Trends Cogn Sci 7:483–488

Zakay D (1998) Attention allocation policy influences prospective timing. Psychon Bull Rev 5:114–118

Zakay D, Block RA (1996) The role of attention in time estimation processes. In: Pastor MA, Artieda J (eds) Time, internal clocks and movement. Elsevier, Amsterdam, pp 143–163