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Comparing the time course and efficacy of spatial and feature-based attention

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Abstract

We investigated the time course of feature-based attention and compared it to the time course of spatial attention in an experiment with identical stimuli and task. Observers detected a speed increment in a compound motion stimulus preceded by cues that indicated either the target location or direction. The cue-target stimulus-onset-asynchrony (SOA) was varied to assess the time course of the attentional effect. We found that spatial attention was deployed earlier than feature-based attention and that both types of attention improved performance to a similar extent at a longer SOA. Results indicate that attention is a flexible mechanism allowing us to efficiently select task-relevant information based on either spatial or feature dimensions, but that spatial attention exert its effects faster.

Keywords: Visual attention; Spatial; Feature; Time course; Psychophysics

1. Introduction

A visual scene contains much more information than we are able to process at once. Attention is needed to select information from the scene for further processing. An important question is 'what is selected?'. Numerous studies have shown that attention can be directed to spatial locations, improving performance for stimuli in the attended location (for reviews, see Carrasco, 2006; Cave & Bichot, 1999; Reynolds & Chelazzi, 2004).

In addition to locations, studies have shown that attention can also select visual features regardless of their location. Since a visual stimulus always occupies a certain spatial location, it is important to control spatial selection. Thus studies of feature-based attention generally use compound stimuli that contain multiple features superimposed in the same spatial location. For example, attending to direction of motion increases neural responses in MT neurons (Treue & Martinez Trujillo, 1999) and human visual cortex (Saenz, Buracas, & Boynton, 2002). There is also psychophysical evidence that feature-based attention improves behavioral performance. Discrimination is better when observers divide attention over two spatially separate dot patterns that move in the same direction than when they move in opposite directions (Saenz et al., 2002). Furthermore, attending to one motion direction in a compound motion stimulus produces a motion aftereffect consistent with the attended direction (Lankheet & Verstraten, 1995).

These studies are demonstrations of the neural and behavioral effects of feature-based attention; much remains unknown about the characteristics of feature-based attention. An important issue yet to be assessed concerns the temporal dynamics of feature-based attention, which is critical in characterizing and understanding the mechanisms underlying this type of attention. In the present study, we adapted a classical cueing paradigm (Posner, 1980) to investigate the time course of the deployment of feature-based attention, by varying the stimulus-onset asynchrony (SOA) between the cue and the target stimuli. This paradigm has allowed researchers to establish that it takes about 200–300 ms to allocate voluntary spatial attention (Cheal & Lyon, 1991; Jonides, 1980; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989). The development of

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the attentional modulation of ERP waveforms was assessed at a fixed cue-target SOA in an ERP study in which observers attended to locations or features (Anllo-Vento & Hillyard, 1996). It was found that ERP modulation had a later onset when observers attended to features than when they attended to locations (but see Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004). However, in this experiment observers always attended to a feature at a specific location, which might induce a bias for spatial selection. Furthermore, there was no behavioral effect of attention as the ERPs were measured for distracter stimuli for which no response was made. The first goal in the present study is to evaluate the speed at which feature-based attention is deployed with explicit behavioral measures and to compare it with that of spatial attention.

The second goal of this study is to compare the efficacy of spatial- and feature-based attention. Spatial cueing effect has been found in virtually all studies, but the status of feature cueing is less clear. Whereas some studies have found an effect of feature cueing (e.g., Baldassi & Verghese, 2005; Brawn & Snowden, 1999; Cooper & Juola, 1990; Lambert & Hockey, 1986), others have failed to find such an effect (e.g., Moore & Egeth, 1998; Shih & Sperling, 1996; Theeuwes, 1989). Some studies have explicitly compared the efficacy of spatial- and feature-based attention (e.g., Baldassi & Verghese, 2005; Shih & Sperling, 1996; Theeuwes, 1989). However, such a comparison is not straightforward because different stimuli have almost always been used in the location and feature cue conditions. In the few cases when the same target and distracter stimuli have been used in both conditions, the physical cue stimuli were different (e.g., Baldassi & Verghese, 2005; Theeuwes, 1989). Furthermore, these studies have used only a single timing condition, which differs across studies, making it hard to compare across studies and to generalize the results. Here we used identical physical stimuli—both the cue and target—and task to assess the effect of spatial and feature cues in the same observers. The only difference between the cueing conditions was the instructions associated with the cues, ensuring that any observed effect would reflect differences in the attentional mechanisms. Including the spatial cue condition also allowed us to compare our measured time course to previous results obtained with various stimulus configurations.

2. Methods

2.1. Subjects

Three trained psychophysical observers participated in the experiment, all with normal or corrected-to-normal vision. Except for one author (TL), observers were naïve as to the purpose of the experiment.

2.2. Visual stimuli

The stimuli were moving dot patterns (dot size: 0.1°, 105 cd/m^2) presented on a dark background (12 cd/m^2). The dots were confined to two circular apertures (diameter: 5.0°) on the horizontal meridian (eccentricity: 7.0°) to the right and left of fixation. Each aperture contained 80 dots, half of which moved to the left and the other half moved to the right (see Fig. 1); all dots moved at 100% coherence. Stimuli were presented on a 21 inch CRT monitor with a refresh rate of 100 Hz.

2.3. Task and procedure

The events in a trial are illustrated in Fig. 1. A fixation point (0.2°, 105 cd/m^2) was displayed in the center of the screen throughout the experiment. After a fixation period of 1.5 s, a brief tone was played to indicate the beginning of a trial. Cues were then presented in the center of the screen for 100 ms to direct observers' attention. The cue was either a single arrow pointing either to the left or to the right, or a double arrow cue pointing to both directions (cue size: 0.9° × 0.07°, 0.5° above the fixation point). In separate blocks, the single arrow cue either indicated the location of the target (spatial: location cue), or the direction of the target (feature: direction cue), with 100% validity (on target present trials). The double arrow cue was uninformative about either the location or the direction of the target and served as a common neutral condition. Each block contained 96 trials, with 48 single arrow cue trials (24 left arrows and 24 right arrows) and 48 double arrow cue trials. At the beginning of each block, a prompt was displayed to indicate whether the single arrow cues in the current block indicated target location or motion direction.

After the cue offset and an inter-stimulus-interval (3 possible values: 50, 200, and 400 ms), the dot patterns were displayed for 300 ms. Observers detected a possible speed increment in one of the dot fields. Dots in one aperture moved at 2.5°/s while dots in the other aperture moved at 4°/s—the baseline speeds; the two baseline speeds were randomly assigned to the apertures on each trial. Two different baseline speeds were used to prevent observers from using a strategy that simply compares the speeds of the two dot fields in different locations when observers were cued to attend to a particular direction (Saenz, Buracas, & Boynton, 2003). On target present trials (50% of trials) there was a speed increment—the dot fields moved at a fixed speed for 100 ms, and then one of the 4 dot fields increased its speed slightly for 200 ms (see bottom diagram in Fig. 1). Observers pressed one of two keys to signal target presence or absence. A low frequency tone was played as feedback after an incorrect response. Observers were instructed to maintain fixation and their eye position was monitored with an infrared video camera system (ISCAN, Burlington, MA). Videos of the left eye were recorded and viewed later to verify proper fixation. All observers maintained stable fixation throughout the experiment.

Each session contained 4 or 8 blocks of trials, half of them location-cued blocks and half of them direction-cued blocks, in a counterbalanced order. The SOA was fixed within a session, but varied in a random order for each observer across sessions.[1] Each observer completed 16 blocks at each SOA, 8 location-cued and 8 direction-cued blocks. A staircase procedure that contained only the neutral cue trials was run before each session to determine the magnitude of the speed increment necessary to achieve a given performance rate. The purpose of the staircase procedure was to set the task difficulty at an intermediate level so that an attentional effect could be observed. Two interleaved staircases were run, one for each target baseline speed, to achieve a hit rate of 71%. This would correspond to a d' of 1.1, assuming neutral criterion (i.e., 29% false alarm) in the detection task. To assess the effect of attention we calculated the *relative* change between the valid and neutral conditions.

3. Results

A signal detection analysis was performed to calculate the d' (sensitivity) and C (criterion, defined as $-(z(\text{hit})+z(\text{false alarm}))/2$)—a measure of bias (Macmillan & Creelman, 2005).

[1] We did not vary SOA within a block because we calibrated neutral performance for each SOA. Interleaving the SOAs would lead to three possible target strengths (magnitude of speed change) within a block, which could be confusing for the observers and led to different strategies.

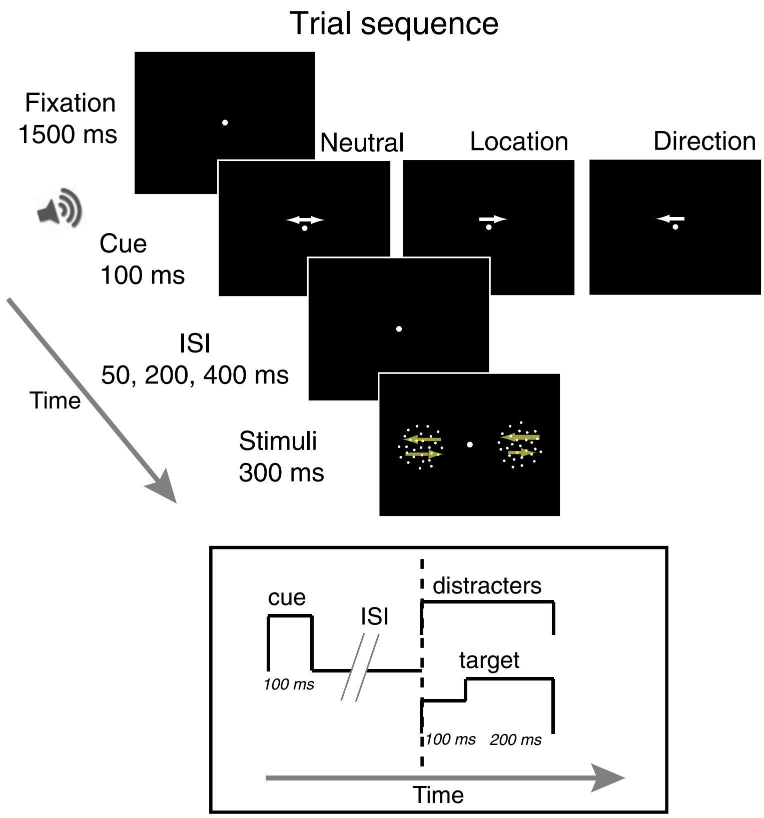

Fig. 1. Trial structure. The bottom diagram indicates the timing of a target present trial; the target was a speed increment for 200 ms in one of the four moving dot fields.

Results from individual observers are shown in Fig. 2. Individual observer data were analyzed via mixed-effects ANOVAs on the 16 blocks of data at each SOA, with cue (location vs. direction) as a between-block variable and validity (valid vs. neutral) as a within-block variable (repeated measures). The ANOVA results are presented in Table 1. Significant effects associated with cue type are difficult to interpret as cues were blocked and there might be slight differences in baseline performance (see Methods). Hence the critical effects are the validity main effect and the cue × validity interaction.

For the d' measure at the 150 ms SOA, neither the validity nor the cue × validity interaction effect was present. At the 300 ms SOA, there was a significant interaction between cue and validity indicating that the location cue improved detection accuracy more than the direction cue (this effect was significant in two observers and marginally significant in one observer). At the 500 ms SOA, both the location and direction cue improved detection accuracy to a similar extent, as all observers showed only a validity main effect.

For the response bias measure (C), there was no consistent overall pattern. There were only a few significant effects in certain conditions, but bias was small and results were not consistent across observers. For example, there were small, opposite bias patterns for the location cue at 300 ms SOA for S1 and S2, with S3 showing no bias pattern, yet all three observers showed similar effects in d'. Thus the bias (when present) and sensitivity did not co-vary.

We further evaluated the relative change in performance due to attention by subtracting d' and C for the neutral condition from those of the valid condition. The group averaged data are plotted in Fig. 3. The results are consistent with individual observer analyses: no benefit in d' at the 150 ms SOA for either cue, benefit for the location cue but not for the direction cue at the 300 ms SOA, and benefit for both cues at the 500 ms SOA. Again, changes in response bias (C) were close to 0 and exhibited no systematic pattern.

It has been shown that task-irrelevant central arrow cues produce involuntary shifts of spatial attention (Hommel, Pratt, Colzato, & Godijn, 2001). This suggests that observers might have inadvertently shifted their spatial attention upon seeing a direction cue, even though they knew that doing so would not benefit performance. Such a strategy could cause a delay in deploying feature-based attention—as we observed here—and would predict a congruency effect: better performance on congruent than on incongruent trials. We analyzed our data according to the congruency between the cue and the target on the uncued dimension, e.g., congruent trial: when a left pointing direction cue was followed by a leftward moving target in the left aperture; incongruent trial: when the same left pointing direction cue was followed by a leftward moving target in the right aperture. We re-plotted the data shown in Fig. 3 according to the congruency on the uncued dimension (Fig. 4). Both congruent and incongruent condition showed

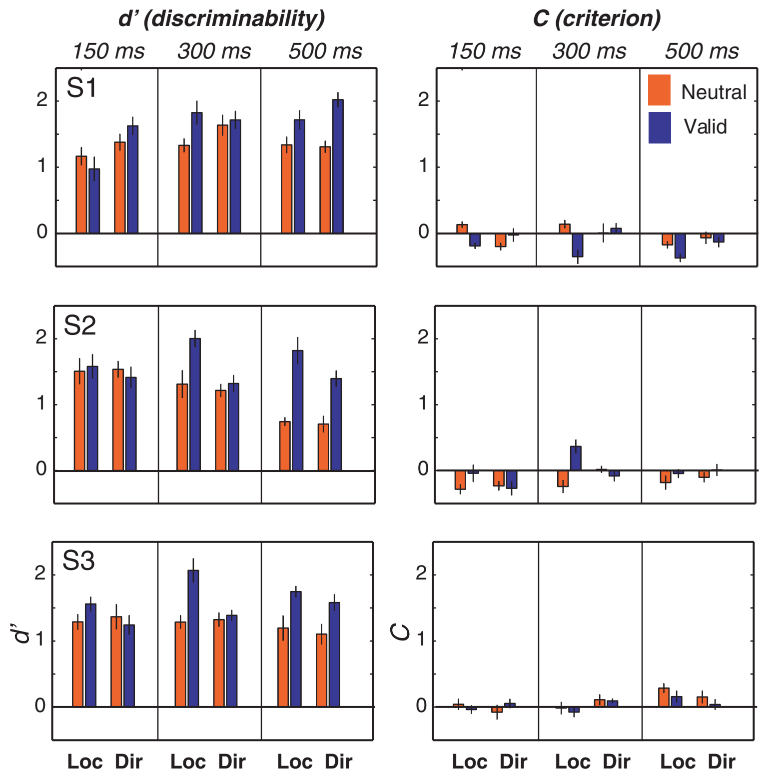

Fig. 2. Individual observer data (S3 is an author, TL): d' and C for each cueing condition and SOA. Error bars are ±1 s.e.m. based on eight observations (blocks). Loc, location cue; Dir, direction cue.

Table 1
Statistical results from ANOVAs for each observer at each SOA and separately for d' and C

	d'			C		
	150 ms	300 ms	500 ms	150 ms	300 ms	500 ms
S1	Cue[a]	Validity[a], cue × validity $p = .07$	Validity[c]	Cue × validity[b]	Validity[a], cue × validity[b]	Cue[a]
S2	ns	Validity[b], cue × validity[a]	Validity[c]	ns	Validity[a], cue × validity[c]	ns
S3	ns	Cue[a], validity[b], cue × validity[a]	Validity[b]	ns	ns	ns

Non-significant effects are not listed (ns indicates none of the effect was significant).
[a] $p < .05$.
[b] $p < .01$.
[c] $p < .001$.

similar cueing effect across SOAs and cue types, for both d' and C. The pattern of results shows no congruency effect. If anything, the d' for the location cue condition at 300 ms SOA was higher in the incongruent than the congruent trials (this effect was largely driven by one observer). This analysis indicates that observers followed instructions and deployed either their spatial or feature-based attention according to the specific cue.

4. Discussion

The main finding of this experiment is that feature-based attention exhibited a slower time course than spatial attention. Cueing target location improved performance at both 300 and 500 ms SOA but not at 150 ms SOA; these results are consistent with the time course of spatial attention found for other tasks (Cheal & Lyon, 1991; Jonides, 1980; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989). We set out to investigate the temporal dynamics of feature-based attention. Cueing target direction did not improve performance at 150 and 300 ms SOA but did so at 500 ms SOA. That is, feature-based attention takes somewhere between 300 and 500 ms to exert its effect. These results are consistent with the ERP study that showed attending to features caused ERP modulation in later time ranges than attending to locations (Anllo-Vento & Hillyard, 1996).

One interpretation of the observed differential time courses concerns the neural mechanisms for the two types of attention. Voluntary spatial attention is thought to be controlled via top-down signals from the parietal and frontal brain areas (Desimone & Duncan, 1995). Given that the early visual cortex is retinotopically organized, spatiotopic modulation is relatively easy to implement in such a system (Itti & Koch, 2001). Feature-based attention, however,

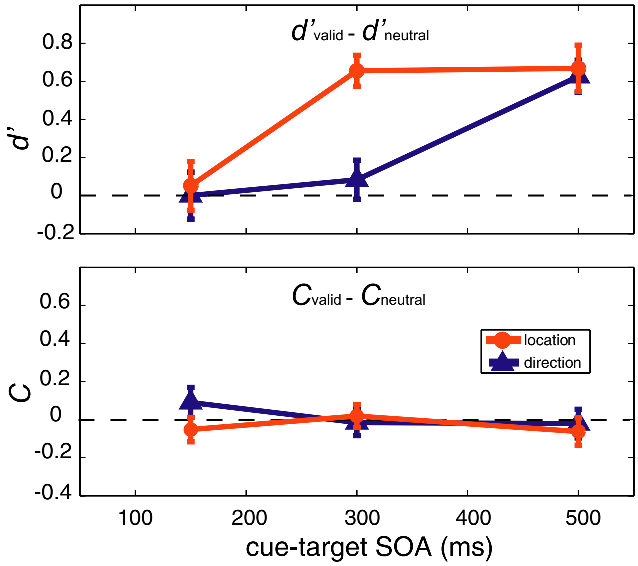

Fig. 3. Group averaged changes in d' and C between the neutral and valid cue condition. Error bars are pooled standard errors across three observers, calculated as the square root of the summed squared standard errors of individual observers, divided by the number of observers.

requires selecting a particular stimulus attribute across multiple spatial locations, which seems more complex to implement in the retinotopically organized early visual cortex. Such modulation might be achieved in later visual areas that are less retinotopically organized and contain neurons with a larger receptive field size, hence it might take a longer time to develop.

Our paradigm also allows us to compare the efficacy of spatial and feature cue more directly than previous studies (Baldassi & Verghese, 2005; Shih & Sperling, 1996; Theeuwes, 1989). In our experiment, the same observers detected a speed increment with identical stimuli with the two cue types; the only difference was the meaning of the cue (location or direction). Furthermore, the cues also conveyed the same statistical information: both cues reduced the number of possible targets by half (from 4 to 2), compared to neutral cues. Thus, it is appropriate to compare the effect of the two types of attention. In light of our results, previous studies that failed to find an effect for feature cueing (e.g., Moore & Egeth, 1998; Shih & Sperling, 1996; Theeuwes, 1989) probably did not provide optimal timing conditions for feature-based attention. For example, Moore and Egeth (1998) used brief, masked displays, and Shih and Sperling (1996) used rapid-serial-visual-presentation, both of which might not have provided sufficient time for feature-based selection to take place.

Our results also have bearing on the issue of whether location is 'special' in selective attention. While some investigators proposed that all stimulus attributes, including location, can equally be utilized in selecting information (e.g., Bundesen, 1990; Duncan, 1981, 1984), others proposed that location is special in that location information assumes priority in selection (e.g., Cave & Wolfe, 1990; Posner, Snyder, & Davidson, 1980; Treisman, 1988). However, the meaning of 'priority' and 'special' is often rather vague. As pointed out by Lamy and Tsal in a review (Lamy & Tsal, 2001), the debate on the status of location in selective attention concerns multiple related, yet distinct, sub-topics. Our results argue against claims of location superiority based on null results of feature cueing (e.g., Moore & Egeth, 1998; Shih & Sperling, 1996; Theeuwes, 1989). Indeed, location and direction cues are equally effective in the 500 ms SOA condition in our experiment. This suggests that attention is a flexible mechanism allowing us to efficiently select task-relevant information based on either spatial or feature dimensions. However, our results do not necessarily challenge the location-special view in that spatial selection might still be a 'default' mode of selective attention, as demonstrated in studies that manipulated task relevance of spatial and feature information (Lamy & Tsal, 2000; Tsal & Lavie, 1993). Indeed, our results suggest that location is

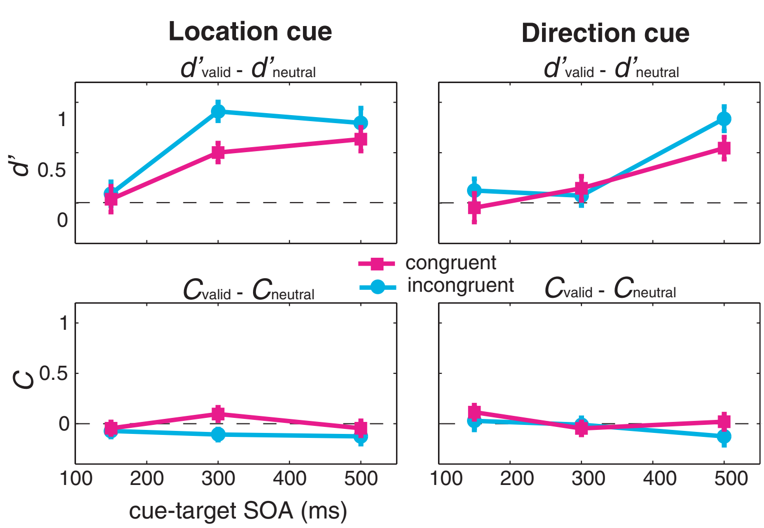

Fig. 4. Same data as in Fig. 3, plotted separately by whether the cue was congruent or incongruent to the target on the uncued dimension. Error bars are same as in Fig. 3.

special in the sense that spatial attention is activated earlier than feature-based attention. Whereas our study is concerned with a particular feature—direction of motion; the paradigm we have implemented to investigate the temporal dynamics of both spatial and feature-based attention can be applied to other feature domains, such as color, size and orientation.

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