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RESEARCH ARTICLE

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# Attentional processing of colour and location cues

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**Abstract** The aim of the present experiment was to investigate attentional processing of colour and location cues using a detection task. Subjects were required to respond to cued corners of a line drawing of a three-dimensional cube. Both cue and target were highlighted in red or green in one corner of the cube. Cues could be valid or invalid with respect to both the colour and location of subsequent targets. Results indicated a significant main effect of location validity, but no main effect of colour validity. Results also indicated that significant colour cueing effects were evident when location cues were invalid. These data also suggested different time courses for the processing of location and colour information. Location validity effects were largest at the shortest interstimulus interval (ISI) and decreased slightly with increasing ISI. In contrast, colour validity effects were absent at the shortest ISI, but thereafter increased with increasing ISI. The results of this experiment indicate that colour cues can be effective even in an inherently spatial task, provided there is sufficient time for the processing of colour information.

**Keywords** Visual attention · Colour cue · Location cue · Detection · Three-dimensional objects · Reaction time

## Introduction

There is a great deal of evidence that prior information concerning the spatial location of a subsequent target facilitates the selection of that target for further visual processing (Eriksen and Hoffman 1973; Jonides 1981; Posner 1980; Posner et al. 1978). It is now also clear that prior feature information (colour, shape, orientation) can also facilitate target processing (Duncan 1981; Humphreys 1981). However, over the last couple of decades there has been considerable debate over the relative importance of spatial versus feature-based visual attention. Thus many researchers argue that stimulus selection via spatial location is primary (see, for example, van der Heijden 1993; Johnston and Pashler 1990; Schneider 1995; Tsal and Lavie 1988, 1993), whereas others argue that location is just one selection attribute among many, including object features such as colour, shape and orientation (see, for example, Bundesen 1990; Duncan 1981; Humphreys 1981; Laarni 1999; Laarni et al. 1996).

Numerous experiments from several different experimental paradigms including discrimination, search, motor tasks and event-related potential (ERP) studies, have demonstrated that selection by location is faster, and/or occurs earlier than selection by object features. Location discriminations can be performed approximately 150–250 ms faster than colour discriminations (Tanaka and Shimojo 1996). Target orientation can be identified earlier if targets are cued by location rather than colour (Laarni et al. 1996). The first observable signs of corrections on movement kinematics following perturbations of target colour or location are evident 80 ms earlier for location than for colour perturbations (Pisella et al. 1998). ERP indices of visual attention are also consistent with faster and earlier processing of location cues. Location effects are visible in ERP waveforms as early as 80–100 ms after stimulus onset, and generally occur between 50 and 100 ms earlier than colour or shape effects. In addition, the effects of feature cues are greater at attended than at unattended locations, and are virtually absent at unattended locations, suggesting that attention to features is dependent on prior attention to locations (Anllo-Vento and Hillyard 1996; Eimer 1995; Hillyard and Münte 1984; Luck et al. 1993).

There is also evidence suggesting that selection by location is an essential, primary stage of attentional

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orienting. For example, although target location can be known in the absence of feature (colour or orientation) information, the reverse is not true (Brouwer and van der Heijden 1996; Johnston and Pashler 1990). Similarly, selection by feature information appears to be mediated by prior selection by location: identification of target location is more accurate than identification of target colour or shape even when targets are cued by colour or shape and not location (Laarni and Häkkinen 1994). Feature conjunction search is thought to be mediated by location, with targets being identified via the locations containing specified feature conjunctions (Isenberg et al. 1990; Nissen 1985; Treisman 1988; Treisman and Sato 1990). There is also evidence that selecting by location is preferred even when target location is completely taskirrelevant (Cave and Pashler 1995; Tsal and Lavie 1988, 1993).

Electrophysiological, anatomical and behavioural experiments have led to the proposal of two separate visual pathways for feature and location processing, respectively. According to this proposal, a ventral stream of projections from striate cortex to inferotemporal cortex is responsible for feature processing and a dorsal stream from striate cortex to posterior parietal cortex is responsible for spatial processing (Goodale and Milner 1992; Ungerleider and Mishkin 1982). Processing of location information via the dorsal pathway, and feature information via the ventral pathway, would provide a neurophysiological basis for faster and earlier location processing because the fast conducting neurons of the dorsal pathway would be expected to result in faster processing than the approximately equal numbers of slow and fast conducting neurons which make up the ventral pathway (Goodale and Milner 1992; Maunsell et al. 1990; Nowak and Bullier 1997; Rossetti 1998).

The above evidence for a special, primary role for selection by location in visual processing seems fairly strong. However, there is evidence that colour cues can be as effective or even more effective than location cues under certain conditions. For example, Laarni et al. (1996) observed equally accurate levels of performance following location or colour cues provided optimal cue lead times (CLTs) were used for location and colour cues (short and long CLTs, respectively). Laarni (1999) found colour cueing effects as large as location cueing effects (both approximately 100 ms) when target and distractor were less easily discriminable (i.e. had the same global shape). Humphreys (1981) found that colour information was processed faster than location information when locations were not easily discriminable (less than 1 degree apart). Hillyard and Münte (1984) found that the hierarchical dependence of selection by colour on prior selection by location disappeared if attended and unattended locations were adjacent. Finally, van der Heijden et al. (1996) found that subjects initially cued to select a target letter by colour preferred to select additional letters by colour rather than shifting to selection by location (as found by Tsal and Lavie 1993), unless performing with free vision and under poor viewing conditions.

Three recent experiments compared location and colour cueing effects using designs which allowed partial investigation of the combined effects of colour and location cues (Laarni et al. 1996; Lambert and Corban 1992; Tsal and Lavie 1993). The results of these experiments indicated a strong overall advantage for location cueing, but also suggested that the effects of location and colour cues can combine to produce greater facilitation when both types of cue are valid. This possibility has implications for the ‘location special’ view because it suggests that although feature cues generally have a smaller impact on performance, they can contribute to improved target identification even in the presence of valid location cues. This contrasts with a possible strong interpretation of the ‘location special’ view that feature information is redundant in the presence of valid location information. However, in the three experiments described above, only indirect evidence for additive effects of location and colour is provided. For example, in Laarni et al.’s (1996) experiment, the effects of a location cue, in the form of an abrupt luminance increment, were compared with those of a feature cue, a colour spot cue and a symbolic colour cue. In Tsal and Lavie’s (1993) experiment, location and colour effects were the result of expectancies based on cue-target location and/or colour concordance, rather than precues. However, direct comparisons seem again inappropriate because of the greater task relevance of colour, which provided the ‘go/no-go’ signals. In fact, subjects were instructed to report a letter in a given location or of a given shape depending on colour cueing. A further complication is that the discrimination tasks used in these three experiments may have increased the likelihood that colour cues would be used even when location cues were valid, because colour information was necessary to identify the target. Thus although there is evidence that the visual system uses location cues in tasks involving detection, discrimination, single feature and conjunction search, the same cannot be said for feature cues. In fact, all of the experiments comparing location and colour cues outlined above used discrimination or search tasks in which colour was necessary for target identification. To our knowledge no one has compared location and cueing effects using a detection task. This may be important since there is evidence that various tasks (detection, location discrimination, moving eyes or arms to target location) are subserved by different mechanisms than feature-based tasks (colour, size, luminance and vernier discrimination; Tanaka and Shimojo 1996).

The present experiment was designed to investigate location and colour cueing effects, using a design permitting direct assessment of possible interactions between them. In addition, a detection task was used to investigate the ubiquity of colour effects (i.e. do valid colour cues enhance performance in the presence of valid location cues on all types of tasks, or is an additional effect of colour cueing restricted to feature-based tasks?). Subjects were asked to respond to the second of two sequentially highlighted corners of a three-dimensional (3D) cube, which were highlighted in either red or green. The second highlighted corner (the target) could be the same or a different colour, and in the same or a different position to the first highlighted corner (the cue). Based on the results of Laarni et al. (1996), Lambert and Corban (1992) and Tsal and Lavie (1993) it was hypothesised that location validity effects would be larger than colour validity effects. It was also hypothesised that there would be an interaction between location and colour validity effects, such that the fastest responses would follow cues which were valid with respect to both location and colour, while the slowest responses would follow cues which were invalid with respect to both location and colour.

## Methods

### Subjects

Twenty students participated in this experiment (ten females and ten males). Subjects' ages ranged from 18 to 24 years. All subjects were right handed, had normal or corrected to normal vision and were na as to the purpose of the experiment.

### Apparatus and stimuli

Stimuli were presented on a 24×32.5 cm Silicon Graphics computer screen. The object used in the experiment was a white line drawing of a 3D 2-$cm^3$ cube appearing against a black background and was generated using a Silicon Graphics $O_2$ workstation. The angle of the cube presentation was such that the front face of the cube was directed approximately 25° to the left edge, and 10° to the lower edge. The angle subtended by the cube was 2° 17′ (Fig. 1). Trials began with the appearance of a white fixation dot in the centre of the screen. This was followed by the cube that appeared in the centre of the screen, superimposed over the fixation dot. After a variable interval the cue appeared, followed by the target. Both the cue and target were a highlighting of one right-angle of the cube in heavy red or green lines (length 5 mm) and could appear on any of the 24 right-angles of the 3D cube. Cube-cue and interstimulus intervals (ISIs) were 200, 400 or 600 ms, and 150, 250 or 350 ms, respectively. Cue duration was 200 ms and target duration was 100 ms. Cube-cue intervals and ISIs were randomised across trials to decrease expectancy effects. The shades of red and green used for the cue and target were isoluminant (16 Cd/$m^2$).

The validity of the cue with respect to both location and colour of targets was manipulated to produce four different types of trials: (1) location valid and colour valid trials (LV-CV) in which the cue was at the same location and the same colour as the target, (2) location valid and colour invalid trials (LV-CI) in which the cue was at the same location as the target, but of a different colour, (3) location invalid and colour valid trials (LI-CV) in which the cue was in a different location to the target, but of the same colour, and (4) location invalid and colour invalid trials (LI-CI) in which the cue was at a different location, and of a different colour to the target. Of all the trials, 70% were valid (LV-CV), 21% were invalid (7% each of LV-CI, LI-CV and LI-CI trials) and 9% were catch trials (i.e. trials in which no target was presented).

Subjects' eye movements were monitored using infrared eye tracking equipment (Applied Science Laboratories, model 210) mounted on an adjustable head-and-chin rest. Trials with horizontal or vertical eye movements greater than 1° of visual angle were automatically discarded and replaced.

### Procedure

The experiment was conducted in a dimly lit room. Subjects were seated comfortably in front of the computer screen with the head

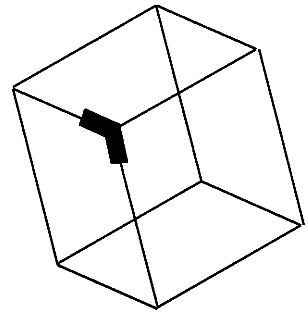

**Fig. 1** Line drawing of cube used in the experiment. Lines were drawn in white against a black background. The cue and target were red or green highlighted corners of the cube (shown here as black)

positioned in an adjustable head-and-chin rest so that the distance between the eyes and the screen was held constant at approximately 50 cm. Each trial began with the appearance of a white fixation dot in the centre of the screen, followed by the appearance of a white line drawing of a 3D cube superimposed on the fixation dot. Shortly after this the cue (highlighting of a corner of the cube in red or green) appeared and a second red or green highlighting of the same or a different corner of the cube (the target) followed. Subjects were instructed to focus on the fixation dot throughout each trial and respond by pressing a button as soon as they became aware of the second highlighted corner. They were told that it was important not to move their eyes away from the fixation dot, and that trials in which they did this would be automatically discarded and repeated. They were also told that on some trials there would only be one highlighted corner, and that if this were the case, they should refrain from pressing the button. Trials were terminated by the subject's response or 2000 ms after target presentation, whichever occurred first. Catch trials ended with a response or 3000 ms after cue presentation. Subjects were given on-screen feedback immediately following trials on which their response was too early or too late. The cube for the next trial was displayed 2 s later.

Each subject performed one practice block before performing the experimental blocks. The subjects performed 660 trials presented in three blocks of 220 trials (462 valid, 139 invalid and 59 catch trials per subject).

### Data analysis

Each subject's data were submitted to the following editing procedures. First, error trials were identified and excluded from the analysis. Error trials included trials in which eye movements occurred, trials with reaction times (RTs) shorter than 150 ms or greater than 2000 ms, and trials for which there was no response, or the response occurred prior to target presentation. Second, trials with RTs outside the range encompassed by the mean ± 3 SD were also eliminated. Errors were not analysed as the numbers of these trials were very low: (a) misses – none, (b) catch trial responses – 1%, (c) eye movements – 1%. Mean RTs for each condition and subject were analysed using a location validity by colour validity by ISI ANOVA. Differences between individual means were assessed using Newman-Keuls *post hoc* procedures.

## Results

### Colour and location validity effects

Results indicated a significant main effect of location validity [$F(1,19)=22.18$, $P<0.0001$]. Subjects were on average 76 ms faster responding to targets following valid as opposed to invalid location cues. The main effect of colour validity was not significant [$F(1,19)=1.12$, $P>0.05$]. Subjects were on average only

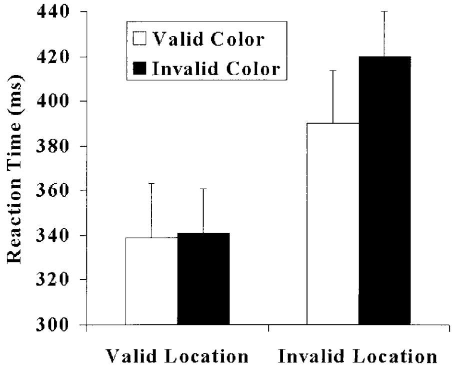


**Fig. 2** Interaction between colour and location validity effects. *Bars* indicate standard error

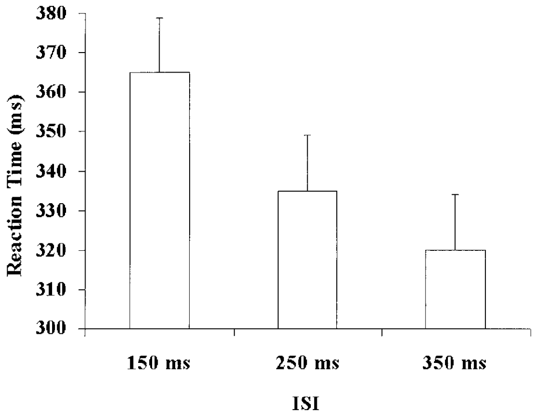


**Fig. 3** Effect of interstimulus interval (ISI) on reaction times. *Bars* indicate standard error

10 ms faster responding to targets following valid as opposed to invalid colour cues. However, there was a significant interaction between the effects of location and colour validity [$F(1,19)=10.32$, $P<0.01$], indicating that the effect of colour validity differed depending on the validity of location cues. Thus, although there was no effect of colour validity when location cues were valid, there was a significant effect of colour validity when location cues were invalid ($P<0.05$). The mean difference between responses to valid and invalid colour cues when location cues were invalid was 14±10 ms (see Fig. 2).

### Effect of ISI

Results of the ANOVA revealed a highly significant main effect of ISI [$F(1,19)=35.76$, $P<0.0001$]. Newman-Keuls *post hoc* tests revealed that responses to targets occurring 150 ms after cue offset were significantly slower than responses to targets occurring either 250 or 350 ms after cue offset ($P<0.01$ in both cases). Responses to targets occurring 250 and 350 ms after cue offset were not significantly different ($P>0.05$). The effects of ISI are illustrated in Fig. 3.

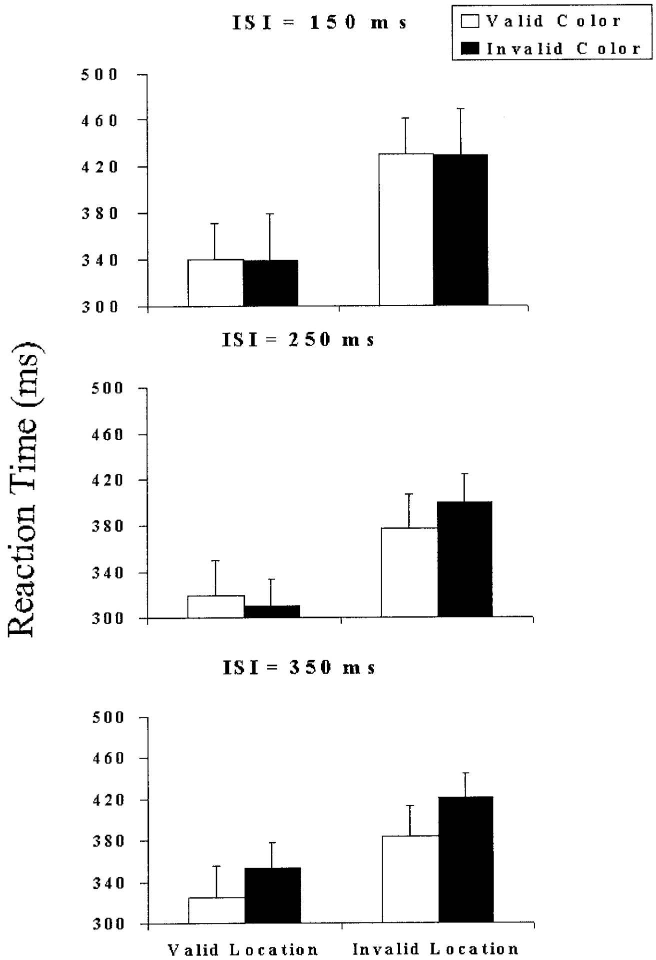


**Fig. 4** Effects of colour and location validity as a function of ISI. *Bars* indicate standard error

### Effects of colour and location validity as a function of ISI

As Fig. 4 shows, the effects of both colour and location validity appeared to differ depending on ISI [$F(1,19)=10.32$, $P<0.001$]. The effects of location validity tended to decrease as ISI increased from 150 to 350 ms ($P$s<0.05). In contrast, colour validity effects tended to increase with increasing ISI. A particularly interesting result was the emergence of a colour validity effect even when location cues were valid at an ISI of 350 ms ($P$s<0.05).

## Discussion

The results of the present experiment supported the hypothesis that location validity effects would be larger than colour validity effects. There was a main effect of location validity, but colour validity effects were significant only when location cues were invalid (indicated by a significant interaction between location and colour validity effects). However, results provided only partial support for the second hypothesis; although the slowest RTs occurred on trials in which both location and colour information was invalid, the fastest RTs occurred on trials with valid location cues irrespective of the validity of colour cues. This pattern of results suggests hierarchical processing of visual information. In other words, valid location cues are sufficient for fast accurate detection responses, so under these circumstances additional colour information is redundant. Colour information only becomes useful if location cues are invalid, when it facilitates detection of targets appearing at unexpected locations. This interpretation is consistent with the results of experiments showing that colour cues have greater effects on responses when location information is unhelpful (Hillyard and Münte 1984; Laarni 1999; see also Lambert and Hockey 1986). It is also consistent with a strong interpretation of the location special view (that feature information is redundant in the presence of valid location information), and with the view that selection by location is not only faster, but also an essential and primary stage of visual attention.

However, it is also possible to explain the above pattern of results purely in terms of faster processing of location as opposed to colour (feature) information, without arguing for the primacy of selection by location. According to this interpretation, colour information is redundant when location cues are valid only because location cues are processed faster than colour cues, which means that a response is made before colour cues can be processed sufficiently to facilitate performance. In contrast, when location cues are invalid, attention must be shifted to a new location in order to locate the target, resulting in a delay before a response can be made. The extra processing time available because of this delay may be sufficient for subjects to use colour cues to help locate the target.

It is not possible to distinguish between these two interpretations on the basis of the results of the location by colour validity analysis reported above. However, the two interpretations make different predictions concerning the pattern of location and colour validity effects as a function of ISI. The first interpretation predicts that colour validity effects should never be significant when location cues are valid, but may be significant when location cues are invalid, regardless of ISI. In contrast, the second interpretation predicts that there should be no colour validity effects at short ISIs, irrespective of location validity, but there should be colour validity effects associated with both valid and invalid location cues at longer ISIs. The pattern of location and colour validity effects as a function of ISI observed in the present experiment tends to support the second interpretation. At the shortest ISI (150 ms) there was no evidence of colour validity effects associated with either valid or invalid location cues, suggesting that there was insufficient time for subjects to use colour cues. With ISIs of 250 ms there was again no colour validity effect when location cues were valid, but a small colour effect was evident when location cues were invalid. At the longest ISI (350 ms) there was a larger colour validity effect when location cues were invalid, and a small colour effect in association with valid location cues. The emergence of a colour validity effect in association with valid location cues at an ISI of 350 ms suggests that the apparent redundancy of colour cues in association with valid location cues is the result of faster processing of location cues. Thus when ISIs are short, and location cues are valid, colour cues are redundant in the sense that there is insufficient time to use them for target detection. In contrast, when ISIs are long, there is a gating effect on the processing of location information: although location cues can be processed much more quickly than colour cues, the target does not appear until sufficient time for some processing of colour cues has elapsed. As a result, small colour validity effects can be observed even when location cues are valid. However, even when different processing times are accounted for, location cues clearly have a much greater effect on response times than colour cues. Even at an ISI of 350 ms, location validity effects were more than four times larger than colour validity effects. It is possible that with longer ISIs, larger colour validity effects might be observed (although these might be counteracted by inhibition of return; Law et al. 1995; Tanaka and Shimojo 1996; Tipper et al. 1994).

On the basis of these results, selection by location does not appear to be a mandatory, initial stage of attentional processing which is always used in preference to selection by feature, as has been suggested by some researchers (Cave and Pashler 1995; Tsal and Lavie 1988, 1993). The fact that colour cues may facilitate performance in association with valid location cues suggests that the visual attention system uses all available information when selecting items for attention, rather than preferring selection by location. In this sense, selection by location is not primary, although it is faster, and has a greater facilitatory effect. This suggests the possibility of a continuum, rather than a strict dichotomy between location and colour processing, which depends on the temporal constraints attached to each visual feature processor. Such a continuum between location and colour processing has already been observed for action control (Pisella et al. 1998).

Although the results of the present experiment clearly demonstrated much larger location validity effects than colour validity effects, it is possible that this was at least partly due to greater difficulty in identifying targets which were the same colour as the preceding cue, particularly when location cues were valid. Thus the absence of colour validity effects when location cues were valid may have occurred because subjects had greater difficulty detecting targets which were the same colour and in the same location as the cue. In other words subjects may have experienced ‘repetition blindness’ (Kanwisher 1991). However, because repetition blindness does not occur at ISIs greater than 200 ms, investigation of this issue requires examination of location and colour validity effects as a function of ISI. If the absence of colour validity effects when location cues were valid was due to repetition blindness, colour validity effects associated with valid location cues should be evident at ISIs of 250 and 350 ms, but not at an ISI of 150 ms. Repetition blindness could also explain the absence of colour validity effects when location cues were invalid at an ISI of 150 ms given that Kanwisher (1991) has shown that second presentations of identical colour patches can be missed even when appearing at different screen locations, although the effect is slightly smaller. The data for ISIs of 150 and 350 ms are consistent with the operation of repetition blindness: colour validity effects are absent in association with both valid and invalid location cues at an ISI of 150 ms, and evident in association with valid and invalid location cues at an ISI of 350 ms. However, repetition blindness cannot explain the absence of a colour validity effect when location cues were valid at an ISI of 250 ms. Although this pattern of results is not entirely consistent with the operation of repetition blindness, it does not rule out the possibility that the absence of colour validity effects at an ISI of 150 ms was due to repetition blindness.

Repetition blindness is usually evident as a failure to respond to targets, although it is conceivable that it could also result in slower responses on some trials. Thus, if repetition blindness affected the results in the present experiment, one would expect to see a greater number of response omissions in the conditions most likely to be affected (i.e. valid colour and/or short ISI). Subjects made very few response omissions so it was not possible to analyse these data statistically. Nonetheless the pattern of response omissions as a function of location and colour validity and ISI is not consistent with the occurrence of repetition blindness. Virtually all response omissions occurred at ISIs of 150 ms, but there did not appear to be more response omissions following valid as opposed to invalid colour cues. When location cues were valid, the greatest number of response omissions occurred when colour cues were *invalid*, and when location cues were invalid similar numbers of response omissions occurred regardless of colour validity. Thus the observed pattern of response omissions indicate that ISI was a more important factor than colour validity. For this reason, it is unlikely that the lack of colour validity effects at short ISIs was due to repetition blindness. Nevertheless, because in the present paradigm cues and targets were presented at identical locations in location-valid trials the repetition blindness alternative could also be described in slightly different terms. That is, the subjects may have found it difficult to distinguish between cue-alone (catch) trials and cue-followed-by-target trials under conditions where cues and targets were identical and the ISI was short. This may have led to delayed responses in some trials. This effect may in turn have counteracted any benefit from colour cueing. This explanation could account for the absence of colour cueing effects for valid-location trials for the 150-ms and the 250-ms ISI condition.

In conclusion, apart from supporting the notion that selection by location is faster and has a greater facilitatory effect than selection by colour, the results of the present experiment provide the first direct evidence of colour validity effects using a detection task. They also show that even when using a task which is essentially spatial, and without instructing subjects to use colour cues to help them locate targets, significant, although small, colour cueing effects are observed. Thus, it appears that subjects use all the information available to them (i.e. both location and feature cues) when selecting items for attention. However, when ISIs are short, selection by feature information may not be possible because of insufficient processing time. Thus significant colour effects were observed only when location cues were invalid (when there was presumably more time available for the processing of colour information). This pattern of results is consistent with the results of many experiments showing that colour cues have greater effects on responses when location information is difficult to resolve (Hillyard and Münte 1984; Laarni 1999). The observed pattern of colour and validity effects as a function of ISI extends previous findings by suggesting that greater colour cueing effects are due to the increased processing time resulting from the invalid location information.

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