Dimension-based attention in visual short term memory

Michael Pilling[1] and Doug J.K. Barrett[2]

[1] Oxford Brookes University [2] University of Leicester

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Author contact:

Dr. Michael Pilling,

Psychology, Faculty of Life and Health Sciences,

Oxford Brookes University,

Oxford. OX3 0BP.

United Kingdom.

Tel: 0044 1865 783788; Fax: 0044 1865 483887; Email: mpilling@brookes.ac.uk

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Authors' note

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Abstract

We investigate how *dimension-based attention* influences *visual short-term memory* (VSTM). This is done through examining the effects of cueing a feature dimension in two perceptual comparison tasks (change detection; sameness detection). In both tasks a memory array and test array consisting of a number of colored shapes were presented successively, interleaved by a blank inter-stimulus interval (ISI). In Experiment 1 (change detection) the critical event was a *feature change* in one item across the memory and test arrays. In Experiment 2 (sameness detection) the critical event was the *absence of a feature change* in one item across the two arrays. Auditory cues indicated the feature dimension (color or shape) of the critical event with a 80% validity; cues were presented either prior to the memory array, during the ISI, or simultaneously with the test array. In Experiment 1 cue validity influenced sensitivity only when the cue was given at the earliest position; in Experiment 2 cue validity influenced sensitivity at all three cue positions. The greater effectiveness of top-down guidance by cues in the sameness detection task is attributed to the more active nature of the comparison process required to detect sameness events (Hyun et al. 2009).

Introduction

Visual short term memory (VSTM) is the capacity to retain visual information in an active form for several seconds after viewing (Pashler, 1988; Luck & Vogel, 1997). A distinct characteristic of VSTM –differentiating it from both iconic memory and visual long term memory– is its restricted capacity. Estimates suggest that a maximum of around three to four objects can be retained at any moment (Vogel, Woodman & Luck, 2001; Cowan, 2001), though there is an ongoing debate over whether this limit is actually manifested in terms of fixed object slots or a more flexible cognitive resource, which allows some trade-off between precision and capacity (see Luck, 2008).

VSTM underlies our ability to visually compare objects over space and time, a function which is necessary for a number of important cognitive operations such as category learning (Marksman & Gentner, 2000). The role of VSTM in mediating visual comparisons can be seen in the *change detection* paradigm (Pashler, 1988; Luck & Vogel, 1997; Vogel et al., 2001). For instance, Vogel et al. (2001), in one experiment presented observers with a memory display containing four to twelve colored squares. The offset of this display was followed, after a 900 ms blank interval, by a test display. On half the trials the test display was identical to the memory display. On the other half one item changed color (e.g. a previously red square became blue). Participants were required to report whether a color change had occurred or not on each trial. When the display contained just four items, change detection sensitivity was relatively high (around 70% correct). However, sensitivity declined markedly as the number of items increased to twelve items, a result that was attributed to limits in the capacity of VSTM (Luck & Vogel, 1997). Other evidence shows that observers are often strikingly poor in their ability to detect changes in naturalistic scenes and multi-item displays, even after viewing the pre- and post-change displays across several iterations, a phenomenon dubbed *change blindness* (Rensink, O'Regan & Clarke, 1997; Rensink, 2000; see Simons & Rensink, 2005, for a review).

The restrictive capacity of VSTM means that it is not just to changes we show blindness to, but also to things *which do not change*. This fact can be demonstrated in the *sameness detection* task (Davis & Leow, 2005; Hyun, Vogel & Woodman et al., 2009; Wilson & Goddard, 2011). This is similar in many respects to the change detection task: a memory array is presented, which is followed after a blank interval by a test array. The key difference, however, is that the critical event is the *absence of a change* (i.e. one item remains the same across the memory and test array while all other items change). Evidence indicates sameness detection is often less accurate than change detection (Farrell, 1985; Taylor, 1976; Davis & Leow, 2005; *cf.* Theeuwes, 2004), an asymmetry that persists even when judgements concern the same memory and test pair given under different task instructions (Hyun et al., 2011).

This advantage for change- over sameness-detection appears to reflect a general tendency for the visual system to be sensitive to the presence of new information (Jonides & Yantis 1988; Christ & Abrams, 2008). The advantage may be a consequence of the way in which the visual system makes comparisons between information held in memory and current input. For change detection, provided the relevant information is held in VSTM, the mismatch between memory and current input generates a transient which draws attention to the change item in a reflexive manner; for sameness detection no such transient is produced by the correspondence between memory and current input, meaning that no bottom-up guidance is given (Hyun et al., 2009). The consequence of this is that sameness events tend to be inherently less salient than do changes.

One thing that is apparent for VSTM comparison tasks such as change and sameness detection is the role played by *attention*. Sensitivity to change or to sameness events tends to dramatically increase when attention, through cueing or other methods, is directed to the location of the relevant item (Rensink et al. 1997; Scholl, 2000; Tse, 2004; Smith & Schenk, 2008; Wilson & Goddard, 2011). What aspect(s) of VSTM processing are susceptible to such spatial attentional influence? One possibility is that attention affects encoding processes. Attention is generally considered the 'gatekeeper' for VSTM; indeed spatial attention seems to be a prerequisite for items to become encoded into VSTM (Sperling, 1960; Avenbach & Corriel, 1961; Wolfe, Reinecke & Brawn, 2006; Awh, Vogel & Ohr, 2006). However, other evidence shows that directions of spatial attention can influence VSTM even after encoding has taken place; cues presented during the retention interval also have a reliable effect on performance. This indicates attentional prioritisation can occur within VSTM in the absence of perceptual input (Griffen & Nobre, 2003; Makovski, 2012; Matsukura, Cosman, Roper et al., 2014). Furthermore, some evidence suggests valid spatial cues can facilitate performance when they are presented concurrently with the test stimulus (Hollingworth, 2003; Beck & van Lamsweerde, 2011). Such late cueing effects are presumably a consequence of *uncertainty reduction* (Luck, Hillyard, Mouloua & Hawkins, 1996), where the cue allows the relevant comparison and decision processes to be limited to the critical location.[1]

Attention is not just spatial in nature. Attention can also be directed to towards specific *feature values* (e.g. red) or *feature dimensions* (e.g color), modes of attentional selection which have been respectively termed *feature-based* and *dimension-based attention* (see Müller, Reimann & Krummenacher, 2003).[2] These modes of selection have been shown to be independent of spatial attention (Mausell & Treue, 2006); their effects seem to be global across the visual field (Hayden & Gallant, 2005; Lustig & Beck, 2012).

The interest of the current paper is with understanding the impact on VSTM processes when attention is directed towards one particular feature dimension. Evidence suggests that dimension-based attention is something which is, at least in part, under endogenous control (Krummenacher & Müller, 2012). Such control can be manifested by task instruction, by the presentation of cues, or by

[1] It must be noted that these uncertainly reduction effects have not been reliably found in all change detection studies which have presented such late cues. These spatial post-cue effects tend to be found mostly in experiments in which the stimuli consist of naturalistic scenes and have been found to be ineffective in experiments where stimuli are arbitrary geometric shapes (Luck & Vogel, 1997; Becker, Pashler, & Anstis, 2000; Sligte, Scholte, & Lamme, 2008; see Beck & van Lamsweerde, 2011 for further discussion of this issue).

[2] This nomenclature is not consistent across the literature. Some authors, for instance, use 'feature-based attention' as a generic term to describe attentional selection of feature dimensions as well as feature values (e.g. Liu et al., 2003; Mausell & Treue, 2006; Flevaris & Murray, 2015)

varying the trial-to-trial probability of the critical feature dimension (Liu, Slotnick, Serences & Yantis, 2003; Meiran, DImov & Ganel, 2012; Töllner, Zehetleitner, Gramann & Müller, 2010; Wolfe, Butcher, Lee & Hyle, 2003, see Memelink & Hommel, 2013).

In the context of VSTM, research has shown performance is affected when attention is directed towards or away from the critical dimension on a given trial or set of trials (Austen & Enns, 2003; Aginsky & Tarr, 2000; Droll, Hayhoe, Triesch & Sullivan, 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003; van Lamsweerde and Beck, 2011; Yang Chang & Wu, 2013). For example, van Lamsweerde and Beck (2011) used a change detection paradigm in which observers had to report which one of several items changed across a memory and test display. The change on each trial could be to an item's color, shape or location. The probability with which the three different types of change occurred was varied across participant groups in an initial block of trials. All participants then completed an additional block in which the three types of change occurred with equal probability. The accuracy with which different types of change were detected in the latter block depended on the frequency with which that change was experienced in the initial trial block by the group; sensitivity tended to be greatest to the most frequently occurring change type. This effect presumably reflects the way observers weighted attention towards the different features in response to the probability manipulation in the initial block.

The dimensional effects identified by van Lamsweerde and Beck (2011) are not restricted to change detection. Pilling and Gellatly (2013) observed similar effects using a different type of VSTM task: an abrupt probe task (Wolfe et al. 2006; Pilling & Gellatly, 2011). In the task participants viewed a display containing 9 to 36 colored shapes. After a delay, a probe occluded one item, and the participant's task was to report a feature of the occluded item (its color or its shape). The report feature varied unpredictably from trial to trial and was indicated by an auditory cue presented simultaneously with the probe's onset. The relative frequency of the color- and shape-report trials was varied across two participant groups. An effect similar to that reported by van Lamsweerde &

Beck (2011) was found: observers were most accurate when reporting the feature dimension with the higher report frequency. This advantage was independent of set size effects, indicating that the attentional effect of the frequency manipulation was global in its extent, influencing all items in the viewed display (Hayden & Gallant, 2005).

Thus there is clear evidence that that dimension-based attention, like spatial attention, can influence the accuracy of VSTM, whether measured in terms of change detection performance or the accuracy with which previously viewed features can be reported. Performance seems to be improved where task conditions bias attention towards the critical dimension for a trial compared to trials where attention is misdirected. However, unlike for spatial attention, the manner in which dimension-based attention influences VSTM has yet to be investigated. For instance in the context of VSTM does dimension-based attention only influence encoding operations, or does it also influence later stage processes, for instance those associated with comparisons and perceptual decisions?

Two perceptual comparison tasks are investigated in pursuit of this question: change detection (Experiment 1) and sameness detection (Experiment 2). In both a memory and test array consisting of colored shapes, separated by a blank inter-stimulus interval (ISI), are briefly presented to observers. In the change detection task observers have to detect a *feature change*: On critical trials the feature value of one object (either on the color or shape dimension) changed across the memory and test displays while all other objects stayed the same. In Experiment 2 (sameness detection) the critical event was the *absence of a feature change*. Here the task was to detect whether any object retained one of its feature values (either its color or shape) across the memory and test displays when all the other features changed. In both experiments a verbal cue indicated the feature-dimension of the critical event on that trial (i.e. the dimension of the feature that changed or remained constant). A valid-invalid manipulation was used to determine cue effectiveness: on most trials the critical feature dimension was validly cued; on a subset of trials cues misdirected attention to the incorrect dimension (Posner, 1980; Wegener, et al., 2008).

The experiments had three specific aims. The first aim was to establish whether dimension-based attention influences VSTM. As we have seen, much of the evidence for this has been based on change- or task-probability manipulations, which arguably conflate top-down attentional effects with those of extended practice. The use of a cueing method in the current experiments provides a more direct measure of the effect of attention itself. The second aim was –by varying cue position– to determine when cueing was effective within the trial sequence. This manipulation was done in order to determine which sort(s) of VSTM processes were influenced by dimension-based attention. The third aim was to determine whether the magnitude and/or character of dimensional attentional effects depend on the nature of the VSTM comparison task. It may be that the influence of dimensional cues is the same irrespective of whether the task involves detection of a change or sameness event. However there are a priori reasons to assume that this is not case. As we pointed out earlier, sameness detection is much harder than change detection, an asymmetry reflecting differences in the nature of the underlying VSTM comparison process involved (Farrell, 1985; Davis & Leow, 2005; Hyun et al., 2009). Thus, while change detection is supported by bottom-up guidance generated from an automatic comparison process, sameness detection is not. Instead sameness detection must instead rely on active comparisons between the visual information held in memory and current input from the test array to detect the critical event. Given this difference between change and sameness detection in terms of bottom up guidance it seems reasonable to expect that the tasks may also differ in their sensitivity to top-down direction of the form given by dimensional cues.

Experiment 1: Change detection

Method

Participants

Twenty-two participants (20 Female) performed the experiment. All had normal – or corrected to normal – visual acuity and reported normal color vision.

Stimuli and procedure

Stimuli were viewed in a darkened backlit room on a 16” Sony Trinitron CRT color monitor (1024×768, 100 Hz) from an approximate distance of 1000 mm. The monitor was controlled by an Intel Pentium-4 PC fitted with a NVDIA GeForce 4 graphics card. The stimuli themselves consisted of outline geometric shapes; each was one of four types (sizes are given in visual angles for the viewing distance): equilateral triangle (1.3° height); cross (1° width × 1° height); ellipse (1.3° width × 1° height); rectangle (1° width × 1.3° height). The line forming each shape was 3 pixels (0.2°) in width. The shapes were one of four colors (luminance in cd/m^2 and CIE 1931 x,y coordinates are respectively given in parenthesis): red, (10.1, .448, .355); green (11.02, .259, .449); yellow (9.63, .467, .455); blue (10.80, .199, .242). The shapes were presented on a neutral grey (34.99, .304, .350) background.

The experiment was conducted using bespoke software written in the BlitzMax programming language (BlitzMax v1.5, Blitz Research Ltd., Auckland, New Zealand). A schematic depiction of the stimulus sequence on each trial is given in Figure 1. Trials began with a brief alerting tone and the presentation of a fixation cross. The fixation cross was shown alone for 600 ms followed by the onset of the memory array. The memory array consisted of six shapes evenly spaced on a notional circle. The notional circle was centred on the fixation cross and had a radius of 237 mm (13.5°). Combinations of shape and color were randomly selected for the individual stimuli in the memory array from the sample of four values for each dimension. This random selection was done with the constraint that there were always at least two different color and shape values in the array. The use of this limited number of stimulus values was to ensure that verbal encoding processes were of limited use in performing the VSTM task. The memory array was presented for 600 ms; it was followed by a 600 ms blank ISI and then the test array, which was also presented for 600 ms.

On no-change trials the test array was the same as the memory array. On change trials the test array was the same as the memory array except that one feature value of one object was different. The different feature value was chosen randomly from the three other possible values for the dimension; for example on a color change trial a red triangle might became a blue triangle; on a shape change trial a red triangle might became a red ellipse. A ratio of 5:1 change to no-change trials was given; color and shape change trials occurred with equal frequency. This ratio was done on the assumption that cues would be most informative on change trials – since only here is the distinction between valid and invalid cues meaningful.

After the test array offset the fixation cross remained on screen until the participant made a response. Participants responded by pressing one of two triggers on a joypad according to whether they thought a change had occurred or not (the left trigger was designated for ‘no’ responses and the right trigger was designated for ‘yes’ responses). Following a response the fixation cross-disappeared from screen and immediate auditory feedback was given. A new trial was instigated after a 500 ms inter-trial delay.

The dimensional cues were in the form of recorded speech enunciating the words “color” or “shape”. The speech was computer-generated but naturalistic. Sound files containing the speech were generated using online software (http://www.fromtexttospeech.com. British female voice ‘Rachel’ selected with a ‘medium’ speech rate). On change trials cues stated the critical dimension with an 80% validity; on no change trials the cue was randomly chosen to state either “color” or “shape” with the constraint that the two cue words occurred with equal frequency. The cue was given at one of three intervals in the trial sequence: (C_1) 500 ms before the onset of the memory array; (C_2) 500 ms before the onset of the test array, i.e. during the ISI; (C_3) simultaneous with the onset of the test array. The cue appeared in each of the three intervals with the same frequency. All sounds were played through loudspeakers located at either side of the computer monitor.

Participants were informed about the validity of the cue and the ratio of change to no-change trials prior to the task. They were told to emphasise accuracy and not speed in their responding. There were 432 experimental trials. Participants were given a demonstration of the trial sequence and then performed 30 practice trials before starting the experiment. In the experiment a short break was given after every 48 trials.

Insert figure 1 about here

Results

A signal detection analysis was performed on the data: correct responses on change trials were designated as hits and incorrect responses on no-change trials designated as false alarms. The hit rate, i.e. the proportion of correct responses on change trials (p[hit]) was calculated separately for valid and invalid trials. From the hit and false alarm rates, *d*-prime (d') was calculated (d' is a response-bias independent measure of sensitivity; see Macmillan & Creelman, 2005). The mean d' for each of the six factorial combinations of conditions is shown in Figure 2.

A 2×3 repeated measures ANOVA was performed on the d' scores. In this the two factors were *cue validity* (valid or invalid) and *cue interval* (C_1, C_2, C_3). A significant main effect was found for cue validity, $F(1,21)=5.48$, $MSE=.105$, $p=.029$, $\eta p^2=.207$, but not for cue interval, $F(2,42)= 0.16$, $MSE=.387$, $p=.853$). The cue validity × cue interval interaction was significant, $F(2,42)= 3.295$, *MSE*=.091, *p*=.047, ηp^2=.136).[3] In order to explore the interaction paired samples *t*-tests were performed between valid and invalid cue trials separately for each of the three cue positions. These showed a significant effect of cue validity for cue position C_1 (*t*[21]=3.90, *p*<.001), but not C_2 (*t*[21]= 0.59, *p*=.561), or C_3 (*t*[21]=0.17,*p*=.871). As a further test Bayes factors were calculated from the paired samples *t*-tests (see Rouder, Speckman & Sun et al., 2009; the default *r*=1 was used in all calculations). For cue position C_1 the analysis confirmed evidence for a cueing effect for interval C_1, (Scaled JZS Bayes Factor = 42.18, meaning that the data are over forty times more probable under the alternative hypothesis –that the valid and invalid trials differ– than the null). For intervals C_2 and C_3 the analysis supported the null hypothesis (for C_2 Scaled JZS Bayes Factor =3.82, for C_3 Scaled JZS Bayes Factor = 4.43; this means that t the null hypothesis was, respectively, nearly four times and more than four times more probable than the alternative hypothesis for these cue positions).

Insert Figure 2 about here

Discussion

The main effect of cue validity shows that the dimensional cues influenced change detection sensitivity. This finding is consistent with previous reports of the effects of dimension-based attention on VSTM tasks (van Lamsweerde & Beck, 2011; Pilling & Gellatly, 2014). Our cue paradigm, in also varying the cue interval, gave some additional insight into the locus of dimension-based effects. Cues influenced change sensitivity when presented prior the memory array but had no discernible effect when presented after this (during the ISI or with the test array). One interpretation

[3] A further analysis was also performed in which p[Hit] and p[FA] was calculated separately for colour and shape change trials. This necessarily halved the number of trials per data-point for the p[Hit] trials and meant that that standard deviations for the separate d-primes tended to be much larger, particularly for the (infrequent) invalid trials. Importantly, however a three way ANOVA (cue validity × cue interval × change type) showed that change type did not significantly interact with any of the other variables. Given this fact, and to maximise statistical power, it is the omnibus ANOVA which is reported.

of these results is that dimension-based attentional influence is restricted to processes associated with encoding into VSTM. However it may simply be, for reasons discussed earlier, that the later presented cues do not convey enough benefit in the context of the change detection task for participants to utilize them. Thus influence on post-encoding VSTM processes might be found in the context of a VSTM task with higher cognitive demands. We considered the sameness detection task one such candidate: The detection of sameness events seems to require a more active comparison process than does the detection of changes (Hyun et al., 2009). As a consequence of this fact sameness detection may be more sensitive to the guidance given by top-down cues regarding the critical dimension. Experiment 2 tested this possibility.

Experiment 2: Sameness detection

Method

Participants.

There were 20 participants (12 female). These were sampled in the same manner and with the same exclusion criteria as for Experiment 1. No participant had taken part in Experiment 1.

Stimuli and procedure.

The same colored outline shapes described in Experiment 1 were used as stimuli. The trial sequence was the same as in Experiment 1. However in the test array, every item changed both its color and shape except on critical trials where one item retained one of its feature values (either its color or shape) across the memory and test array. The new value for each feature was selected at random from the three other possible values for that feature dimension. A schematic depiction of the trials sequence in Experiment 2 is given in Figure 3. Participants were instructed to report whether or not any item retained the same feature in the memory and test displays. Pilot work showed that performance was no better than chance when (as in Experiment 1) displays contained six items; this pilot data further indicated performance fell within the same range as the change detection task when the set size was reduced from six to three items. Aside from these changes, the trial sequence was the same as Experiment 1. A ratio of 5:1 sameness to no-sameness trials was given. On sameness trials the verbal cue indicated the critical dimension with an 80% validity; on no-sameness trials the cue was random with the constraint that the two words ('color' and 'shape') were given with equal frequency. Cues occurred equally often in each of the three positions. Auditory feedback was given immediately after the response. Demonstration examples were given to ensure that the task was understood. After the demonstration each participant did 30 practice trials before starting the main experiment.

Insert figure 3 about here

Results

The same signal detection analysis was performed as previously described for Experiment 1. The hit and false alarm rates and calculated *d*ˈ are reported in Figure 4. A two-way repeated measure ANOVA (cue validity × cue interval) was performed on the *d*ˈscores. Analysis showed a significant main effect of *cue validity*, $F(1,19)=22.128$, $MSE=.249$, $p<.001$, $\eta p^2=.538$, but not *cue interval*, $F(2,38)=2.171$, $MSE=.149$, $p=.128$. The *cue validity* × *cue interval* interaction was significant, $F(2,38)=3.881$, $MSE=.085$, $p=.029$, $\eta p^2=.170$.[4] Paired samples t-tests were performed between valid and invalid trials. These showed a significant effect of cue validity at all three cue positions

[4] As with Experiment 1 a further analysis was also performed in which scores were calculated separately for colour and shape change trials. This again resulted in highly variable dˈ scores across participants. A three way ANOVA demonstrated that change type did not significantly interact with the other two variables. For the same reasons, as discussed for Experiment 1, it is the omnibus ANOVA that we report in the results.

(C_1,*t*[19]=4.01, *p*<.001; C_2, *t*[19]=4.45, *p*<.001; C_3, *t*[19]=2.69, *p*<.05). A subsequent Bayes Factor analysis of the t-test results further confirmed the existence of a cueing effect for all three cue positions (Scaled JZS Bayes Factors for $C_{1,}$ C_2 and, C_3 are, respectively, 47.05, 113.54, and 3.77, thus in the most limiting case, C_3, the alternative hypothesis was almost four times more likely than the null).

Insert Figure 4 about here

Discussion

As found with change detection, valid dimensional cues improved detection sensitivity. However, for sameness detection this effect was not restricted to the earliest cue position; cues remained effective even when presented as late as with the onset of the test array.

General Discussion

Our two experiments showed that dimensional cues influence VSTM performance. Sensitivity tended to be higher for both change detection and sameness detection when cues validly indicated the dimension for the critical event. The cue position manipulation exposed differences between the change and sameness detection tasks in terms of the locus of their effect. For change detection, cues influenced sensitivity only when they were presented in the earliest cue position, before the onset of the memory array. This fact suggests that the influence of dimension-based attentional in this task was restricted to the encoding stages of VSTM. By contrast, for sameness detection, cues influenced sensitivity at all three given positions. This shows that, in this task at least, dimension-based attention influenced encoding as well as later-stage VSTM processes.

We attribute these differences in cue effectiveness to the different manner in which change and sameness events are processed by the visual system. In a change detection task, any difference between an object's features and its representation in VSTM will generate a mismatch between memory and current input. It has been shown that the occurrence of such a mismatch generates a bottom-up signal, which directs attention to the change (Hyun et al., 2009). Given this bottom-up guidance towards the change item, there may be little benefit to be obtained from being informed about the change dimension in terms of the nature of the comparison process. Consequently participants may simply ignore the cues (or otherwise fail to utilise them to actively modulate their attention) when these cues are presented after stimulus encoding.

For sameness events the situation is different. Here no such reflexive mismatch signal is generated when a feature *does not* change. Because of this lack of bottom-up guidance observers must rely on active comparisons between memory representations and current input in order to detect the sameness event (Hyun et al., 2009). We suspect that it is because of the deliberative nature of the comparison process in sameness detection that observers exhibit greater sensitivity to top-down influence. It should be noted that the specific implementation of the sameness detection task in Experiment 2 makes the perceptual comparison process particularly challenging for the visual system. In most versions of the sameness detection paradigm only one feature dimension is manipulated. For instance in Davis & Leow (2005) participants had to detect the presence of a disk which remained constant in color across two displays when all other disks changed their color but not their shape. Thus variation in the display was always limited to values from a single feature-dimension. In the current study participants had to detect sameness in a *single feature* when variation in the display occurred across two feature-dimensions. Thus in our task the sameness item, like all the other display items, was always physically different in some way across the two displays.

To detect the sameness feature the observer needs to deliberatively compare the feature values of the respective objects on each of the two possible dimensions. It is likely the respective feature dimensions of objects can only be compared in a serial manner (Egeth, 1966; Sternberg, 1998). The cue information could, therefore, be used to prioritise the order in which the comparisons occur in the two feature dimensions. When the cue is valid this prioritization of the appropriate dimension might increase the likelihood of the critical sameness being identified before any time-based decay of the memory representations (van Lamsweerde & Beck, 2011).

This above account explains the effectiveness of cues at position C_2 in the sameness task; it does not so easily account for the cues continued effectiveness at position C_3. Here the cue, by occurring simultaneously with the test array gives no prior information to influence the comparison process. Instead we suspect the main effect of this late cue is in influencing decision processes which occur following any feature comparisons (Wilken & Ma, 2004; Yang, 2011). For instance, the cue might be used to weight evidence concerning the existence or absence of a sameness toward that derived from the comparison process on the cued dimension. The effect of this weighting, when cues are valid, would be to reduce the amount of decision noise leading to an increase in task sensitivity (Smith & Radcliffe, 2009).

Fundamentally, our results show how top-down knowledge about the feature-dimension on which a defined perceptual event is likely to occur influences our sensitivity to that event. In this respect our findings are similar to ones reported in the context of pop-out search (e.g. Müller et al., 2003, Töllner et al. 2010). Here it has been shown that a valid top-down cue that specifies the dimension on which a singleton is defined facilitates detection of that singleton. For instance Müller et al. (2003) presented a verbal cue prior to the onset of a search display that specified an upcoming target dimension with 80% validity. On valid trials there was a clear benefit in reporting the singleton both in terms of response times and accuracy. In this visual search literature, such dimensional effects have been largely attributed to the top-down control of early signal enhancement processes, which occur prior to any spatial selection operations (Found & Müller, 1996; Gramann et al., 2010; Töllner, Müller & Zehetleitner, 2012). It is possible that early signal enhancement processes partly underlie the cue effects found on our two VSTM comparison tasks. Indeed this signal enhancement could be the mechanism by which feature-dimensions are prioritised during VSTM encoding; this difference in signal strength determining the fidelity of the respective feature values in the subsequent memory representations. In the case of the change detection task, such sensory enhancement processes of the kind already reported in visual search might wholly explain the effects of dimensional cues. For the sameness detection task, however, as we earlier described, it seems that cues influence additional aspects of VSTM beyond the encoding stage.

As a final point it should be noted that our results constitute evidence against a strong version of the integrated object hypothesis (Luck & Vogel, 1997; Vogel, et al., 2001; cf. Olson & Jiang, 2002). Results from both experiments indicated that objects in VSTM were not necessarily represented as complete entities; instead what aspects of an object are represented seems to depend, at least in part, on the attentional state of the observer. What our cueing manipulations seem to show is how limited VSTM capacity and process resources can be prioritized by the visual system in a flexible manner in order to meet the observer's current goals. Indeed previous work has similarly claimed that the feature contents of VSTM can vary according to top-down directed goals (Burmester & Wallis, 2011; Davis & Holmes, 2005; Droll et al., 2005). Our results suggest, at least in the case of sameness detection, that this top-down influence is not just limited to how objects are initially represented, but may also extent to later feature comparison and decision processes associated with these representations. Further research will be needed to more precisely elucidate the mechanisms involved in these different sorts of dimension-based attentional influence on VSTM processes.

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Figure headings

Figure 1. Diagram of the trial sequence in Experiment 1. The three cue intervals (C_1, C_2, C_3) are indicated in the trial sequence; note that only one cue was ever given on any one trial. In the example (clockwise from the top) the memory array contains a green cross, blue circle, red cross, green circle, red triangle and a yellow rectangle. In the trial the critical change event is present in the form of a shape change: in test array all items are identical to the memory array apart from the yellow rectangle becoming a yellow circle.

Figure 2. Results from Experiment 1. The mean hit rate (p[HIT]) for valid and invalid trials is shown in plate A; the mean false alarm rate (p[FA]) is in plate B; the across participant mean d' for valid and invalid trials is in plate C.

Figure 3. Diagram of the trial sequence in Experiment 2. As for Experiment one the three cue intervals (C_1, C_2, C_3) are indicated in the sequence. Note that there are only three stimuli in the memory and test array. In the memory array are (clockwise from the top) a green triangle, yellow circle, and green rectangle. In the test array the three objects have changed: the green triangle has become a red rectangle the yellow circle has become a green circle, and the green rectangle has become a blue cross. In the example the critical sameness event is present; here it occurs on the shape dimension (the 'circle' shape being retained in the second of the described objects).

Figure 4. Results from Experiment 2. The mean hit rate (p[HIT]) for valid and invalid trials is shown in plate A; the mean false alarm rate (p[FA]) is in plate B; the across participant mean *d*ʹ for valid and invalid trials is in plate C.

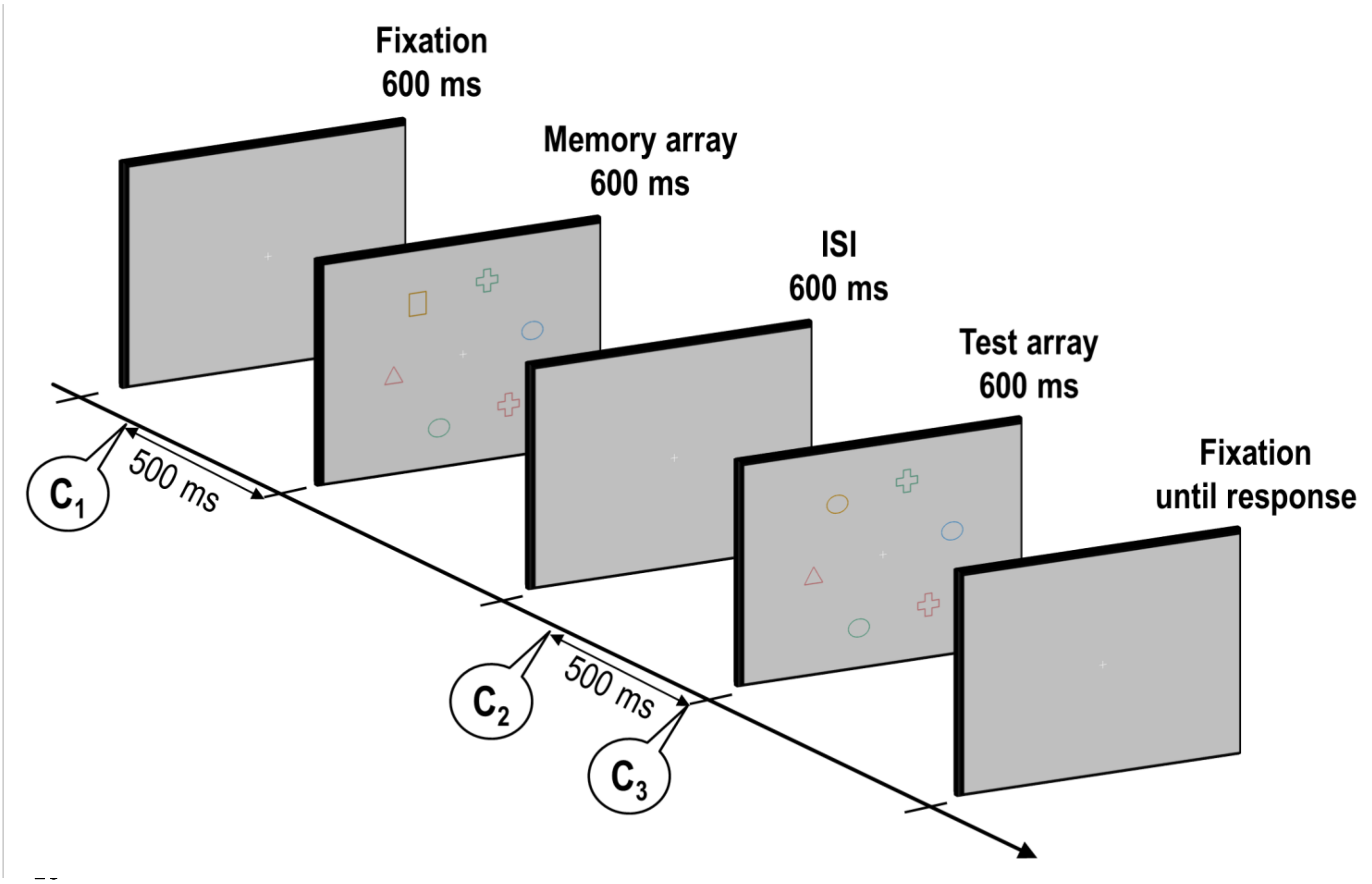
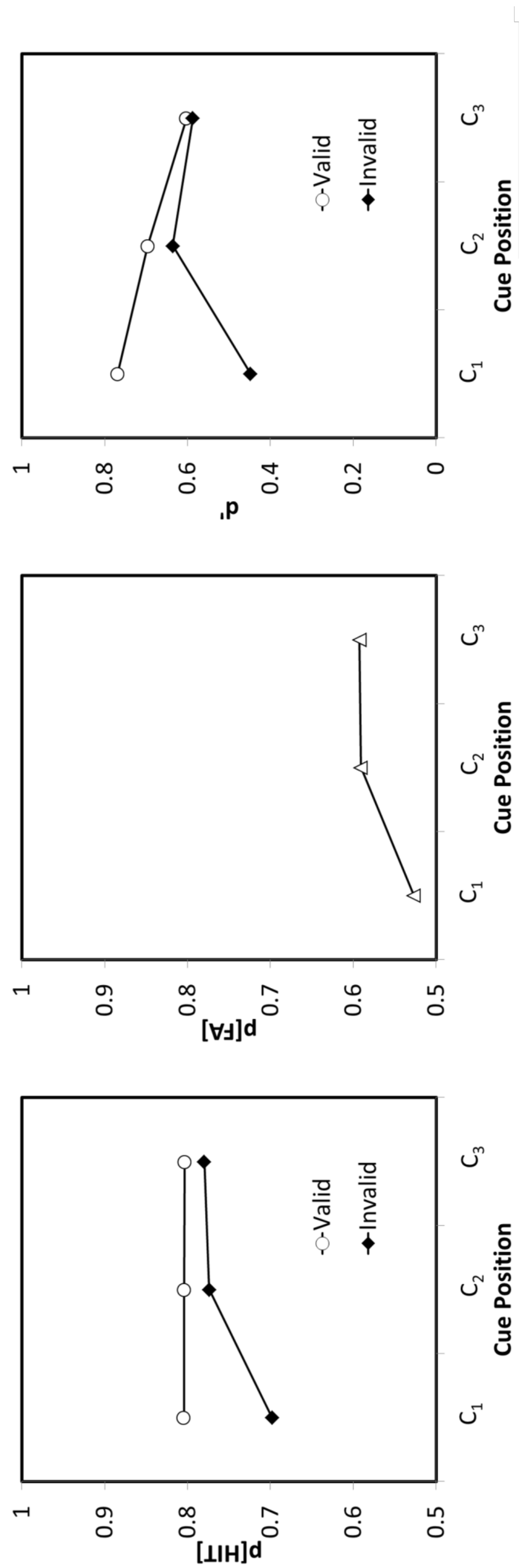

Fixation
600 ms
Memory array
600 ms
ISI
600 ms
Test array
600 ms
Fixation
until response
C1
500 ms
C2
500 ms
C3

Figure 1.



p[HIT]
Cue Position
Valid
Invalid
p[FA]
Cue Position
d'
Cue Position
Valid
Invalid

Figure 2.

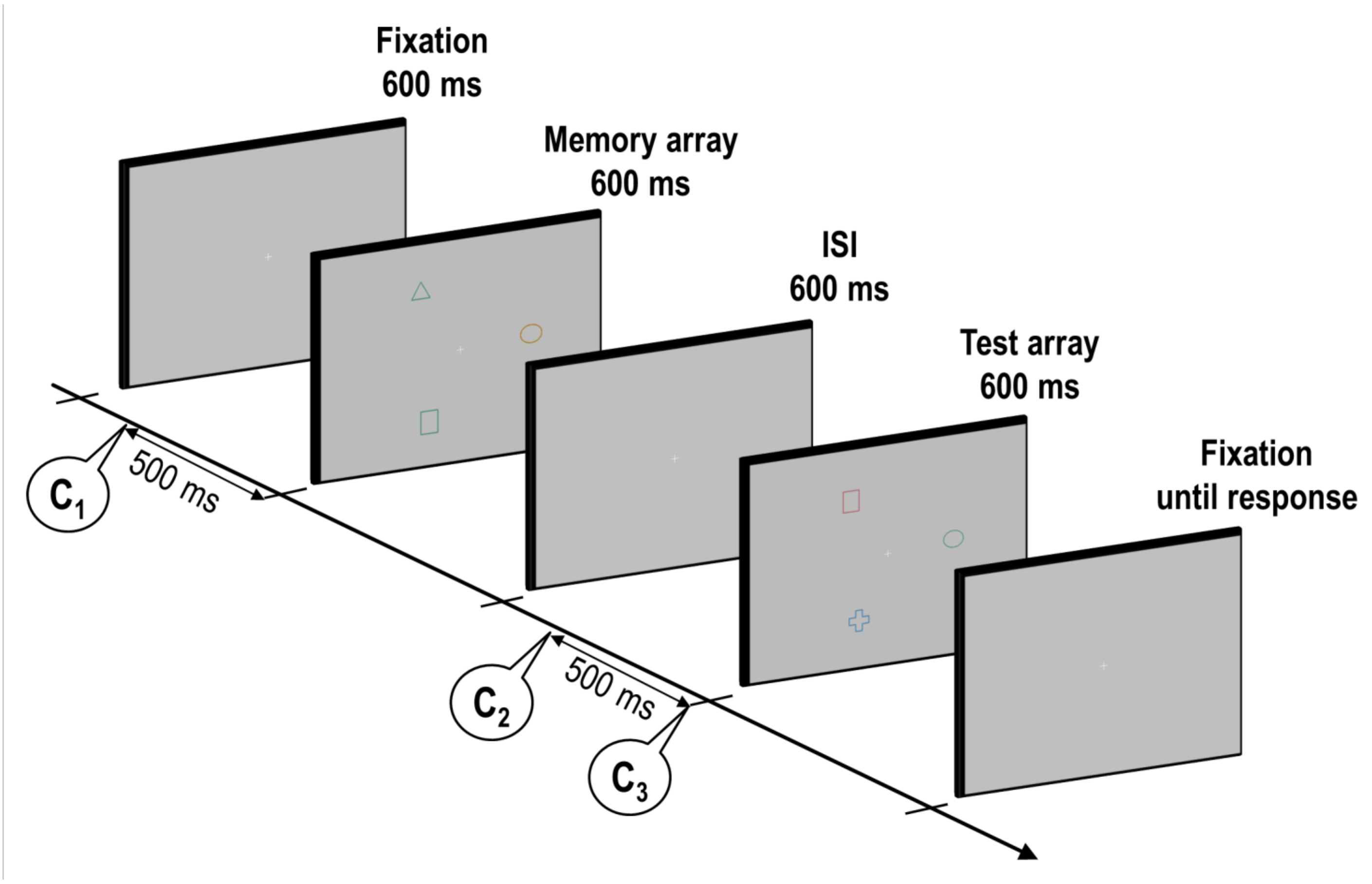

Fixation
600 ms
Memory array
600 ms
ISI
600 ms
Test array
600 ms
Fixation
until response
C1
500 ms
C2
500 ms
C3

Figure 3.

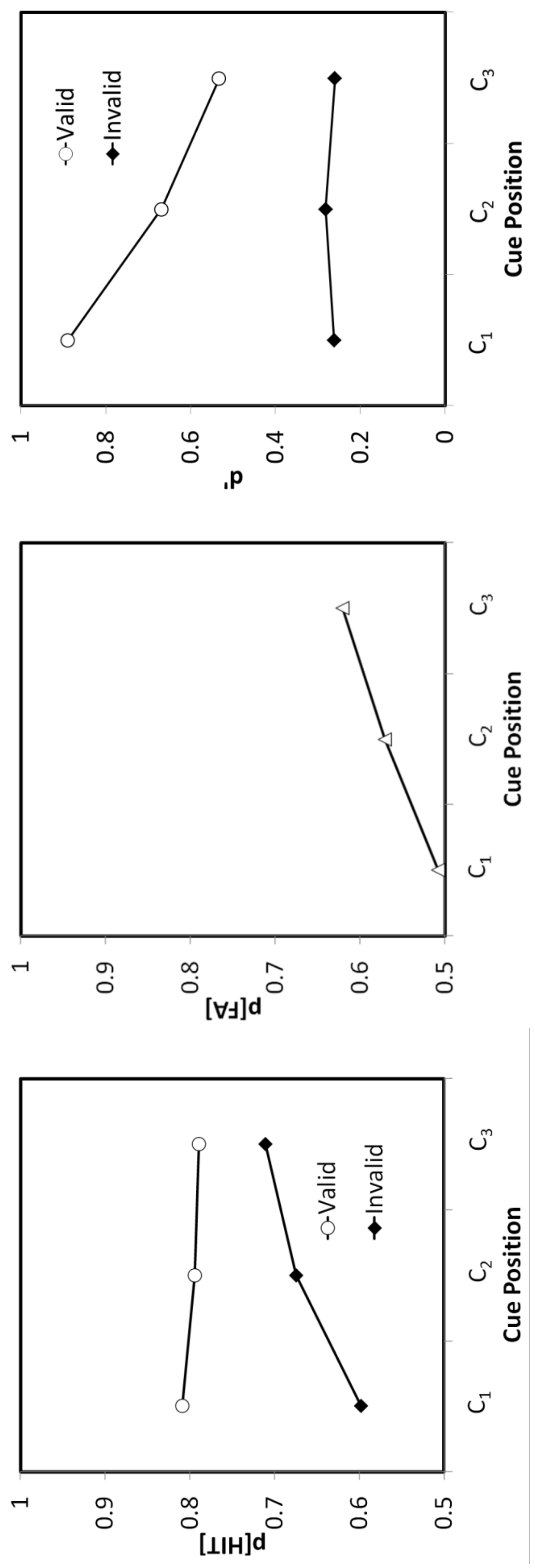

p[HIT]
Cue Position
C1 C2 C3
Valid
Invalid
p[FA]
Cue Position
C1 C2 C3
d'
Cue Position
C1 C2 C3
Valid
Invalid

Figure 4.