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Brief article

Splitting attention across the two visual fields in visual short-term memory

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ABSTRACT

Humans have the ability to attentionally select the most relevant visual information from their extrapersonal world and to retain it in a temporary buffer, known as visual short-term memory (VSTM). Research suggests that at least two non-contiguous items can be selected simultaneously when they are distributed across the two visual hemifields. In two experiments, we show that attention can also be split between the left and right sides of internal representations held in VSTM. Participants were asked to remember several colors, while cues presented during the delay instructed them to orient their attention to a subset of memorized colors. Experiment 1 revealed that orienting attention to one or two colors strengthened equally participants' memory for those colors, but only when they were from separate hemifields. Experiment 2 showed that in the absence of attentional cues the distribution of the items in the visual field per se had no effect on memory. These findings strongly suggest the existence of independent attentional resources in the two hemifields for selecting and/or consolidating information in VSTM.

1. Introduction

The ability to maintain visual information in an accessible state is a critical aspect of our cognitive capacities as it allows us to interact successfully in the visuo-spatial world. Because our visual short-term retention system (i.e., visual short-term memory – VSTM) is extremely limited in storage capacity (Luck & Vogel, 1997), only a subset of information from our extrapersonal world can be transferred into this limited memory space at any one time. The selection of this subset of information is made by attentional mechanisms that can be voluntarily or involuntarily oriented to particular locations or objects. For example, when spatial attention is cued to a particular location of the visual field, the object that occurs at that location will be more likely transferred into VSTM as compared to the other objects (Makovski & Jiang, 2007; Schmidt, Vogel, Woodman, & Luck, 2002).

During the last 10 years, an increasing number of studies have revealed that once transferred into VSTM, the internal representations remain highly flexible and can be selectively accessed and consolidated by attentional mechanisms (e.g., Delvenne, Cleeremans, & Laloyaux, 2010; Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Vecera, 2007; Nobre et al., 2004). Those studies use the *retro-cuing paradigm*, in which an attentional orienting cue was presented during the retention interval of a memory task and pointed to the location of one of the items held in VSTM. Memory for the cued item is found to be better as compared to memory for the uncued items. This finding is crucial as it suggests that it is possible to orient spatial attention onto a subset of internal representations beyond the phase of perceptual encoding. Because spatial location plays a central role in the maintenance of objects in memory (e.g., Jiang, Olson, & Chun, 2000), directing attention to one location previously occupied by an object helps solidify and/or retrieve that object from memory. However, this ability to attentionally select locations already held in VSTM appears to be more constrained than orienting attention in perception. In a

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recent study, Makovski and Jiang (2007) directly compared the effect of orienting attention to multiple locations before (pre-cuing) and after (retro-cuing) the appearance of a memory array. They found that while up to three attentional cues could be used effectively when presented before the memory array, only a single cue was advantageous for memory performance when presented after the offset of the memory array. Although this, along with previous studies (Awh & Pashler, 2000; Kraft et al., 2004; Kramer & Hahn, 1995), indicates that spatial attention can be oriented onto multiple locations at once in perception, Makovski and Jiang's study suggests that orienting attention in memory may be restricted to a single location.

Here, we report an exception to this restriction. We show that attention can be split in VSTM between the left and right visual fields. Specifically, the present study reveals that two non-contiguous locations can be selected from VSTM at no extra cost as compared to a single location, but only if they are from separate hemifields. Past work has demonstrated that attention can be split in perceptual space between the two hemifields at a lower cost as compared to within the same hemifield. This has been observed in a number of visual tasks, such as tracking objects (Alvarez & Cavanagh, 2005), remembering spatial locations (Delvenne, 2005) and orientations (Umemoto, Drew, Ester, & Awh, 2010), matching stimuli (Kraft et al., 2004; Sereno & Kosslyn, 1991), enumerating objects (Delvenne, Castronovo, Demeyere, & Humphreys, 2011), and identifying targets (Awh & Pashler, 2000), amongst others. In particular, performance at those tasks was better when the to-be-attended items were distributed across the left and right visual fields as when they were all displayed within the same hemifield. Here, we provide the first evidence that attention can also be split beyond perception, namely between the left and right sides of internal representations.

2. Experiment 1

2.1. Method

Sixteen volunteers took part in this experiment (9 women; mean age = 21.4, range 20–24 years). In all experiments, the participants had normal (self-reported) or corrected-to-normal visual acuity and normal color vision. They were tested individually in a quiet room with dim lighting.

Visual stimuli were generated by a 3.00 GHz PC and displayed on a 17″ screen. The script was generated by E-Prime programming software (Psychology Software Tools, Inc., www.pstnet.com) and responses were collected using the computer keyboard. Six highly discriminative colored squares (blue, green, pink, red, turquoise, and yellow), produced by permutation of the presence or absence of red, green and blue phosphors, were used as stimuli. At a viewing distance of approximately 60 cm, each square subtended a visual angle of 0.76° x 0.76°. The stimuli were randomly located equidistantly at eight different possible positions on an imaginary circle (7.12° in diameter) centered at fixation. The eight locations were 12:45, 2:15, 3:45, 5:15, 6:45, 8:15, 9:45, and 11:15 o'clock locations. The colors were selected at random with the constraint that two contiguous colors could not repeat. A gray background was used to reduce afterimages.

On each trial, participants were first presented with an initial central fixation cross that they had to fixate throughout the entire trial. After 800 ms, the memory array was presented for 150 ms, followed by a 1000 ms blank interval, then by a cue array for 50 ms, followed by another 1000 ms blank interval and finally by the probe that remained present until a response key was pressed. There were three retro-cue conditions. In the *one-cue condition*, the cue array consisted of a single cue (i.e., a white outlined square subtending $0.76 \times 0.76°$) randomly positioned at one of the eight locations. In the *bilateral-cues condition*, the cue array consisted of two non-contiguous cues located in opposite hemifields. In the *unilateral-cues condition*, the two non-contiguous cues were located within the same hemifield. The distance between the cues was kept constant in both the *bilateral-* and *unilateral-cues conditions* and they were always separated by an uncued location. The cue(s) indicated the location of the test probe (validity = 100%). To measure the effect of retro-cuing on memory capacity, a fourth condition was used in which no cue was presented. In this *no-cue condition*, the memory array was presented for 150 ms, followed by a 1000 ms blank interval and then immediately by the probe. Fig. 1 illustrates the four conditions. Participants were instructed to indicate whether the test color was the same as, or different from the one that was located at the same position on the memory array (with 50% probability). The next trial was automatically initiated 500 ms later.

The conditions were randomly mixed during the experiment and there were a total of 48 trials in each condition. The whole experiment consisted of 192 experimental trials, evenly divided into six 32-trial blocks. Each block began with the presentation of three digits that participants were required to repeat aloud as quickly as they could throughout the block. This concurrent articulatory suppression task was used to discouraged participants from verbally recoding the visual information (Baddeley, 1986).

2.2. Results and discussion

We computed A' from signal detection theory (Aaronson & Watts, 1987; Grier, 1971; Pollack & Norman, 1964) to assess the accuracy of the memory performance for each condition and for each participant. To obtain a second representation of the results, we also measured Cowan's K (Cowan, 2001), an estimation of memory capacity. Fig. 2a and b show the A' and K values, respectively, in each condition. Because the analyses on K produced the same pattern of statistical significance as A', we report only the statistical results on the A' values. The ANOVA (repeated measures) on accuracy (A') revealed a main effect of condition, $F(3,45) = 4.25$, $MSE = 0.007$, $p < 0.01$. Pairwise comparisons showed no difference between the *one-cue* and *bilateral-cues conditions* ($p = 0.60$) and no difference between the *unilateral-cues* and *no-cue conditions* ($p = 0.84$). However, both the *one-cue* and *bilateral-cues conditions* were significantly better performed ($p < 0.05$) than the *unilateral-cues* and *no-cue conditions*. In addition, no difference was found between the left and right visual fields ($p = 0.30$) and