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Working memory and the guidance of visual attention: Consonance-driven orienting

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Two experiments investigated the potential role of the content of working memory in guiding visual attention. Experiment 1 showed that maintaining a shape in working memory resulted in a decisive preference for moving attention to the same shape in the background when those shapes were task irrelevant. Experiment 2 showed a similar preference for words that were semantically related to an item held in working memory. We suggest that keeping an item active in working memory automatically results in a tendency for attention to be "attracted" to stimuli that are related to that item either visually or semantically.

The top-down control of attention has been studied extensively in experimental psychology. In the typical study, subjects are instructed to perform a task, and the instructions for this task determine what subset of the stimuli are to be considered task relevant and what subset are to be considered task irrelevant. Most often, subjects are asked to attend to stimuli satisfying some explicit criterion of selection and to ignore all other stimuli. Modern theories of attention are based largely on the results of such studies. Although this kind of research helps to illuminate the mechanisms for control of attention, it leaves some very basic issues unanswered about how attention is controlled in daily life. After all, outside of the laboratory, people often wander around lacking any explicit intention to attend to, find, or ignore anything in particular. How is attention controlled when an observer has relatively diffuse goals?

Although modern attention theory has had little to say about the spontaneous allocation of attention, some writers on attention from the beginning of the 20th century discussed it at great length. One such writer, Oswald Külpe (1893/1909; see also Pillsbury, 1908), suggested a possible general principle of top-down control: "Impressions which repeat or resemble ideas already present in consciousness are especially liable to attract the attention" (p. 439).

Taking this idea a bit further, some have recently suggested that the activation of semantic representations—whether conscious or unconscious, whether resulting from immediate sensory inputs or from internal trains of stimulus-independent thought—may cause attention to be drawn toward any stimuli in the sensory fields that would tend themselves to activate related concepts (Moores, Laiti, & Chelazzi, 2003; Pashler & Shiu, 1999). This notion (which will be termed *consonance-driven orienting*) can be summarized crudely as the principle "attend to any object that is in any way related to any currently active mental contents." Such a strategy might be useful in coordinating the covert and overt deployment of attention with other ongoing mental activity and might therefore be a very primitive and widespread mechanism for top-down attention control. The principle also seems potentially congenial to a contemporary neurally inspired perspective on attention known as *biased competition theory* (Desimone & Duncan, 1995; Duncan, 1996).

Relevant Findings

In a test of one aspect of the notion of consonance-driven orienting, Pashler and Shiu (1999) instructed subjects to form a mental image of an object (e.g., a tiger). Subjects then viewed a rapid serial presentation of eight line drawings. The task was to search for a target digit that was interposed between the line drawings. One of these drawings depicted an object of the same category as the object just imagined (e.g., a drawing of a tiger). The presence of this item produced an "attentional blink" effect; that is, there was an impairment in the detection of a digit that followed the tiger in the sequence. The result suggests that people cannot help but attend to any object belonging to the same category as some object that they just imagined. In a similar study published soon after, Downing (2000) also showed that a replica of faces or contents presented to the subject and stored in working memory seemed to draw attention even when there was no incentive for this.

In another recent study, Moores et al. (2003) had subjects search rapid serial visual presentations for target objects and examined the effect of including items that were semantically but not visually related to the target (e.g., a vase when the target was flowers, a banana when the target was a monkey). The presence of these target-related items generally delayed correct rejection responses on target-absent trials and produced some increase in the false-alarm rate. The items were also better remembered

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when subjects performed a free recall at the conclusion of the trial. As the authors pointed out, the results are consistent with the possibility that activation of the target caused visual attention to be drawn to related items. However, subjects were searching for these targets, so the results do not necessarily show that activation of one concept is sufficient to cause related tokens to capture attention.

Other data consistent with consonance-driven orienting can be found in some recent studies by Stolz (1996, 1999). Stolz (1996) had subjects make judgments regarding characters that appeared either above or below fixation. When the character position was cued by a word that was semantically related to a prior word that was presented at fixation, the spatial cuing effect was enhanced. Thus, it may be that attention remained locked to the position of a word/cue longer when that word was semantically primed. In a later study, Stolz (1999) showed subjects a prime word and then had them judge the order in which two words were presented. If a word was semantically related to the prime, it tended to be reported as having occurred earlier.

In yet another potentially relevant experiment that was motivated by rather different goals, Dark, Vochatzer, and VanVoorhis (1996) showed subjects a prime word followed by two words (one above the other). One of the target words was semantically related to the prime word. Subjects attempted to report both target words. When they reported only one word, it tended to be the one related to the target. The same effect occurred in an experiment where subjects attempted to report only a single, spatially cued word; again, the word that was semantically related to the prime tended to be reported. This tendency might reflect consonance-driven orienting (although it could probably also be attributed to processes confined to the word recognition process itself).

The Present Study

Using relatively conventional selective attention tasks, the studies reviewed above showed either impairments or improvements in performance that at least potentially conform to what one would expect from consonance-driven orienting. Therefore, these results certainly provide some support for this notion. However, the magnitude of changes or shifts induced by consonance-driven orienting in these studies has usually been very modest. Moreover, as noted above, some of the effects documented in these studies do not necessarily reflect changes in attentional orienting and others fall short of showing that attention is drawn to inputs that are merely related to (rather than identical to) the contents of working memory. Thus, existing data do not show that consonance-driven orienting has anything more than a comparatively trivial functional importance in daily life. However, in these prior studies, consonance-driven orienting was always competing with some other powerful source of top-down attentional control. When such simultaneous attentional control is absent—as is usually true in daily life—it might be the case that consonance-driven orienting can exert a decisive influence over the direction of attention.

In this study we intended to test whether consonance-driven orienting can wield a strong influence when competing strong attentional demands are absent. In Experiment 1, the subjects retained in working memory a certain shape (the *prime shape*) that was tested later within the same trial. After they had viewed the prime, three shapes (termed *background shapes*) were presented. Subjects were explicitly instructed that these shapes would have nothing to do with the memory task. Simultaneously with or slightly after the onset of the three background shapes, three digits were presented. Each of these digits was spatially superimposed on one of the shapes. Subjects were instructed to note and remember any one of the three digits they wished (and subsequently to report it, as described below). They were explicitly instructed that remembering any one of the three digits would be considered as desirable as remembering any other. Next, one test shape was shown and the subjects reported whether this was identical to the prime shape. The purpose of this test was to make sure the subjects did actively maintain the prime shape in working memory. Finally, the subjects reported the test digit that they had elected to store. The basic question was whether visual attention would be drawn to one background shape when it was identical to the prime shape, thus causing the test superimposed on that shape to be reported more often than the other two background shapes.

GENERAL METHOD

Subjects

Undergraduates from the University of California, San Diego, received credit in a psychology course for their participation in this project. There were 23 subjects in Experiment 1A, 21 subjects in Experiment 1B, and 44 subjects in Experiment 2. They all had normal or corrected-to-normal vision.

Apparatus

Stimuli were presented on a 1,024 × 768 MAG DX-15T color monitor controlled by an Intel Pentium IV 1.8 G computer. Subjects viewed the displays from a distance of about 60 cm and entered responses using the keyboard. The program was written in Microsoft Visual Basic 6.0 and was run in Microsoft Windows 98 (second edition) using timing routines that were calibrated with a digital timer.

Stimuli and Procedure

The event sequence of one sample trial is shown in Figure 1. In the description below, we will always use random shapes (Experiment 1) as examples. Each trial began with a small fixation cross presented for 400 msec in the center of the screen. After a short blank interval (400 msec), the white prime shape appeared in the center of the display. The prime shape remained present for 800 msec. Next, the background shape array appeared simultaneously with the disappearance of the prime. The details of the prime and background array will be described in connection with each individual experiment. The three shapes in the background shape array were evenly spaced with their centers on a circle that had a radius of 4.1º. The locations of these shapes on the circle were randomized from trial to trial. The onset of the green digits was later than the onset of the background shape array for a certain stimulus onset asynchrony (SOA). Note that if SOA = 0, the shape and the digits were simultaneous. The SOA between background shape array and test digits will be noted in the presentation of each individual experiment. The green digits were superimposed on the background shape array. The three digits (0–9) were each randomly generated with the constraint that they were different from each other. The digits were presented for 400 msec, and then both background shapes and digits disappeared and a test shape appeared in the center and remained until response. Subjects compared the test shape with

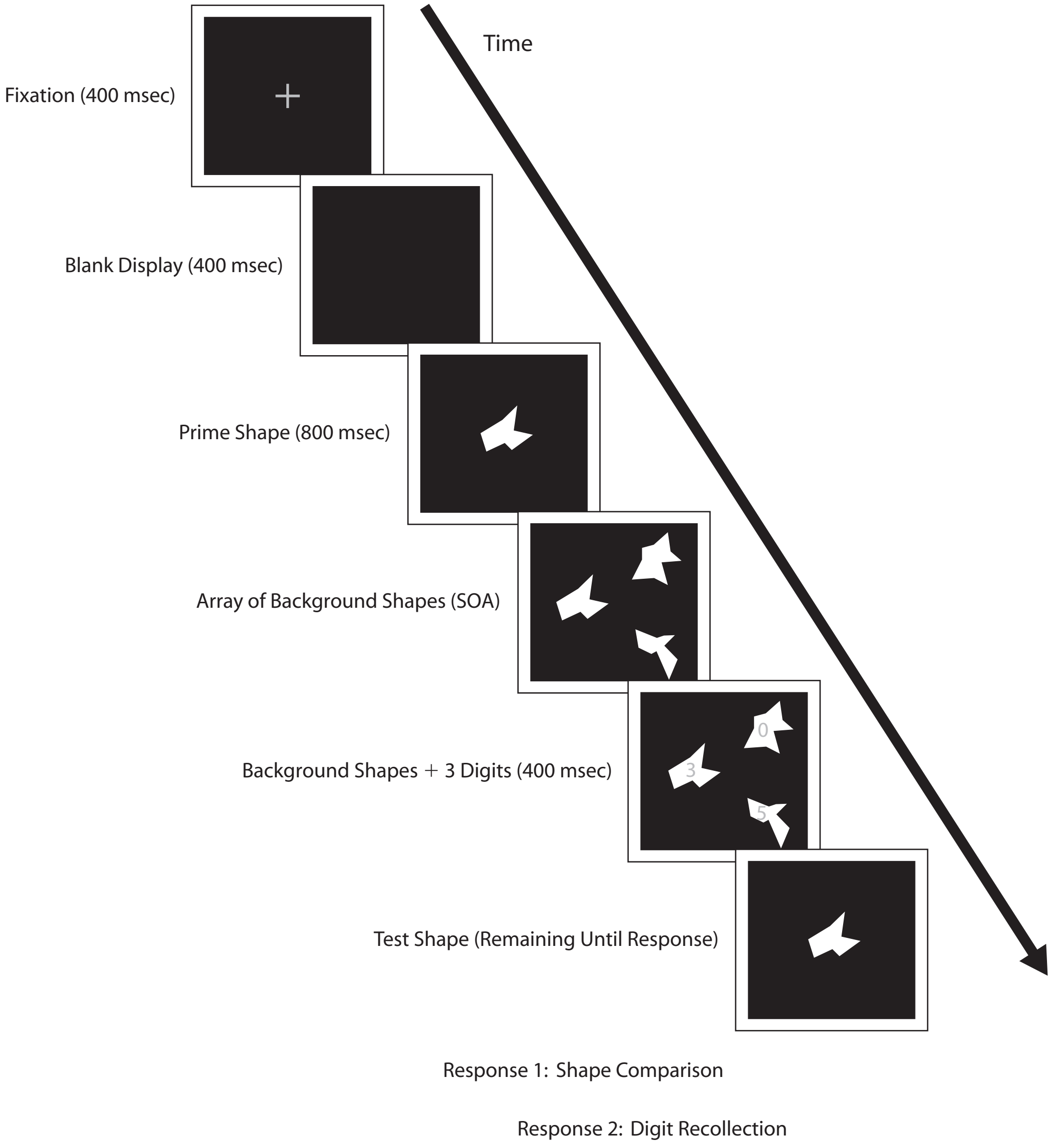

Figure 1. Event sequence of one trial in Experiment 1.

the prime shape. This test shape was randomly chosen to be identical to or different from the prime (50% chance of each). When it was different from the prime, a completely new shape was used.

Subjects were told to respond as accurately as possible in all experiments. They were instructed to fixate the cross and subsequently memorize the prime and any one of the three digits they chose. After the test shape was presented, they indicated whether it was identical to the prime by pressing the "d" or "f" key on the keyboard. Next, they reported the digit they retained by pressing the digit key on the keyboard. The second response triggered the next trial after 800 msec.

EXPERIMENT 1

In Experiment 1, subjects were instructed to retain one random shape in working memory. The question of interest was whether that would cause attention to be drawn to the location in which that shape was repeated in a set of three items that required no response, despite the explicit instructions that made this display irrelevant.

Method

The algorithm to generate random shapes is depicted in Figure 2. Ten random distances (randomly chosen from 0º to 2.7º) were generated and these were combined with 10 angles (0º, 36º, 72º, 108º, 144º, 180º, 216º, 252º, 288º, 324º) to determine the positions of 10 dots in polar coordinates. Then the 10 dots were connected with line segments and the region was filled. Thus, all shapes were freshly created from an essentially unbounded set.

One shape in the background array (hereafter termed the *critical shape*) was identical to a shape that had been used earlier in the experiment. On about 10% of trials, the critical shape was identical to the prime presented on the current trial. When it was not identical to the current prime, it was identical to a prime on a previous trial. The number of intervening trials between appearances of the critical shape was one of the following choices: 0 (the current trial), 1 (the previous trial), 2, 4, 8, 16, 32, 64, 128, or 256 (only in Experiment 1A). Each choice was equally likely unless it was not possible (e.g., the 10th trial could not have a repetition at lag 16 or more). In Experiment 1A, the SOA between the three probes and the test digits was 0; in Experiment 1B, it was 800 msec.

Figure 2. Generation of random shapes used in Experiment 1. Top panel: Ten distances (randomly chosen from 0º to 2.7º) were generated and combined with ten fixed angles (0º, 36º, 72º, 108º, 144º, 180º, 216º, 252º, 288º, 324º) to determine ten dots in polar coordinates. Middle panel: Adjacent pairs of dots were connected with line segments. Bottom panel: The region within was filled in to create the shape.

Each subject participated in six blocks of 50 trials, with the first block excluded from data analysis.

Results

In Experiment 1A, the error rate for the shape comparison task was 7%. The error rate for the digit report task was also 7% (i.e., on 7% of trials, the subject reported a digit that was not one of the three in the background array). In Experiment 1B, the error rate for the comparison task was 5% and the error rate for the digit report task was 2%. These relatively low error rates show that subjects were indeed generally retaining the shape and choosing a digit from the display.

The likelihood of reporting a digit from the critical shape in Experiment 1 is seen in Figure 3. One can see that the likelihood of reporting a digit from the critical shape (rather than from one of the other two shapes in the background array) was substantially higher than chance level [chance level, .33; Experiment 1A, .45, $t(22) = 4.12$, $p < .0005$; Experiment 1B, .77, $t(20) = 9.73$, $p < .0001$] if the prime for that shape appeared within the same trial. But the likelihood of reporting a shape did not differ from chance levels when it was identical to a prime located in previous trials. This result supported the notion that consonance-driven orienting is exclusively a function of working memory rather than long-term memory, be it implicit or explicit.

The same-trial effect of prime match was substantially larger when the shapes preceded the digits by 800 msec (Experiment 1B) than when they occurred simultaneously (Experiment 1A) [$F(1,42) = 36.17$, $p < .0001$]. Therefore, consonance-driven orienting seems to unfold over a reasonable fraction of a second.

EXPERIMENT 2

In Experiment 1, what was memorized was the random shape. In Experiment 2, words were used to determine whether a decisive effect of consonance-based orienting could be driven by lexical semantics as well as resemblances of shape.

Method

In Experiment 2, there were three words presented in the background array on each trial: one that was related to the prime (criti-

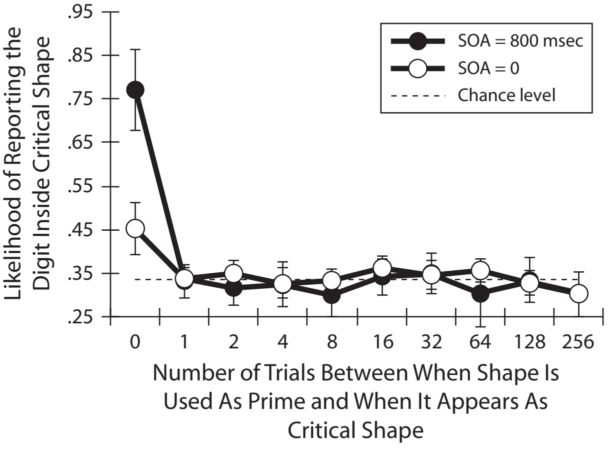

Figure 3. Results of Experiments 1A & 1B. The probability of reporting the digit within the critical shape is significantly higher than chance if the critical shape is identical to the prime shape of the same trial. But there is no such effect when the critical shape is identical to the prime shape of any earlier trials. The consonance-driven orienting is substantially larger when the SOA is 800 msec (Experiment 1B) rather than 0 (Experiment 1A).

cal word) and two that were unrelated. The test word matched the prime word 50% of the time; otherwise, it was an unrelated word. Experiment 1 showed no effect when the critical item was related to a prime from an earlier trial. Therefore, the critical word was always related to the prime of the current trial in Experiment 2, and intertrial relationships were not included. In Experiment 2, the critical word was semantically related to the prime but had no similarity in shape. For example, the prime might have been *atom* and the critical word *molecule* (the complete list is available on request from the authors). Much as in Experiment 1, the digits were superimposed on the top of the words. The digits were green and the background words were white, so the digits remained fairly readable (as confirmed by the very high accuracy that will be reported shortly). The digits appeared to slightly reduce the readability of the words, but degradation of the words could only work to reduce the findings described below. In Experiment 2, we examined the effect of SOA between the onset of the words and the onset of the embedded digits more systematically (comparing 400 msec, 800 msec, 1,600 msec, and 3,200 msec). Each subject participated in six blocks of 38 trials, with the first block excluded from data analysis.

Results

In Experiment 2, the error rate for the comparison task was 3%, and for the digit report task it was 2%, confirming that subjects were indeed retaining the word and choosing digits from the display. The likelihood of reporting the digit that was superimposed on the critical word in Experiment 2 is given in Figure 4. There is a preference for reporting a digit on the critical word in general [$t(43) = 2.44$, $p < .02$]. As shown in Figure 4, the likelihood of reporting from the critical word was significantly higher than chance for all SOAs except 400 msec. The probability of reporting from the critical word increased as SOA increased from 400 msec to 800 msec [$F(1,43) = 7.69$, $p < .01$], but showed no further significant increases as SOA grew from 800 msec to 3,200 msec [$F(2,43) = 0.18$].

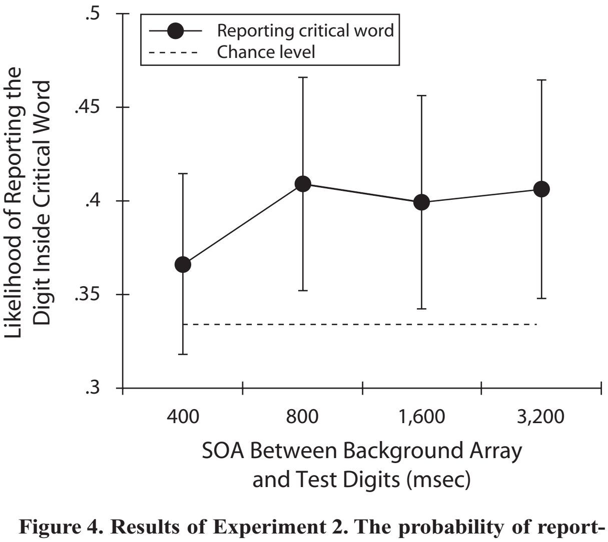

Figure 4. Results of Experiment 2. The probability of reporting the digit within the critical word is significantly higher than chance level. The consonance-driven orienting grows when the SOA (between probes and test digits) increases from 400 msec to 800 msec, but shows little evident increase thereafter.

GENERAL DISCUSSION

When people are retaining shape or semantic information in working memory, there is an apparently automatic tendency for visual attention to shift to whatever object in the background has the same shape as, or bears some semantic relationship to, the contents of working memory. This tendency illustrates what we have termed consonance-driven orienting. This finding is consistent with previous reports (Downing, 2000; Pashler & Shiu, 1999). However, the present work goes well beyond those studies in showing that consonance-driven orienting can play a decisive role in the control of attention. As was noted in the introduction, previous reports on consonance-driven orienting have all shown quite small effects. Plausibly, that is because in these studies there was a powerful form of top-down attentional control in place, and consonance-driven orienting had to compete with this. When no competing top-down set is in place, it appears that consonance-driven orienting can easily play a decisive role in attention control: In Experiment 1B, the consonance-driven orienting increased the chance of reporting the critical shape from the chance level (33%) to 77%. The results also go beyond the work of Pashler and Shiu (1999) and Downing (2000) in showing that the effects "spread" to encompass inputs that are semantically related to the primes. In Experiment 2, in which prime and critical word were linked only by a semantic association, the probability still increased to 40%.

However, consonance-driven orienting appears confined to stimuli that are related to the prime that is currently being retained in working memory. Even the prime from the last trial, which had only occurred a few seconds earlier, did not have any clear-cut effect. This indicates that consonance-driven orienting is far more transitory than certain other forms of priming effects, such as negative priming (Tipper, Weaver, Cameron, Brehaut, & Bastedo 1991) or various forms of repetition priming. This finding further reinforces the view that consonance-driven orienting is not the same as perceptual repetition priming; the former reflects a tendency to shift attention to a certain type of stimulus, whereas the latter reflects a facilitation of the identification process.

The present study also sheds some light on the time course of consonance-driven orienting. In Experiment 1, the consonance-driven orienting was much larger when the SOA was 800 msec rather than 0 msec. Similarly, there was more priming at the 800-msec SOA as compared with the 400-msec SOA in Experiment 2. On the other hand, the results of Experiment 2 suggested that an SOA longer than 800 msec does not cause consonance-driven orienting to grow any further. One may surmise that even though visual perception and attentional orienting can take place much more rapidly in many situations, consonance-driven orienting unfolds in a comparatively leisurely fashion, requiring about 1 sec to fully materialize.

One might argue (as a reviewer of an earlier version of the present article suggested) that instead of automatic attraction of attention to the memorized item, the present results occur because subjects actively seek to find the memorized item in the display—precisely in order to help them remember it. This account might potentially explain the results of Downing (2000) as well. It is not clear whether this should be seen as an alternative explanation of the phenomenon reported here or as a possible functional explanation for why it occurs. To disentangle this account from the automatic view advocated here, one might feel it necessary to arrange things so that people maintain something in working memory, but have no desire to avoid losing it. Most accounts of working memory contend that working memory storage is inherently voluntary, so this may be intrinsically impossible. In addition, this account seems a bit stretched with respect to Experiment 2. There, the prime never occurred among the three test words, and it seems doubtful that searching for and finding a semantically related word really would facilitate maintaining the memorized item; one might even expect similar materials to produce strong interference (see, e.g., Neely & LeCompte, 1999).

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