



the visual analog: evidence for a pre-attentive representation across saccades

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THE VISUAL ANALOG:
EVIDENCE FOR A PRE-ATTENTIVE REPRESENTATION
ACROSS SACCADDES

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Abstract

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Earlier research supports the idea that transsaccadic memory involves a relatively sparse and abstract representation with little detail, much like visual short-term memory (VSTM) within a fixation. We examined whether transsaccadic memory is restricted to VSTM representations or whether it also includes a maskable, short-lived, and more detailed representation, referred to as the visual analog. First, a within-fixation change detection experiment is reported, aimed at clarifying the distinction between VSTM and the visual analog, and also the relationship between the two components. We then report 4 transsaccadic change detection experiments that make use of a modified version of the blanking paradigm originally introduced by Deubel et al. (Vision Research, 1996). The results support the idea that transsaccadic memory includes a VSTM representation for attended objects (i.e., the saccade target) and a visual analog component for both attended and non-attended objects.

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3 Because only a small fraction of the human retina is able to provide the high
4 resolution needed for detailed visual processing, observers move their eyes about three to four
5 times per second. With each eye movement or saccade, the retinal projection of the outside
6 world changes position, bringing an initially peripheral region of interest into foveal vision
7 (De Graef, Christiaens, & d'Ydewalle, 1990; Henderson & Hollingworth, 1999). During a
8 saccade, the image moves very rapidly across the retina. Visual information extraction is
9 therefore mainly limited to fixations or periods in between saccades when eye position is
10 relatively stable. It can be assumed that the visual system somehow integrates the
11 informational contents of individual fixations (e.g., Pertzov, Avidan, & Zohary, 2009; Van
12 Eccelpoel, Germeys, De Graef, & Verfaillie, 2008). How much and what kind of information
13 is retained and integrated across a saccade has been the topic of debate.
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29 An early hypothesis proposed that highly detailed point-by-point representations,
30 produced during individual fixations, could be superimposed or fused to form an image-like
31 representation containing information from multiple fixations (e.g., Breitmeyer, Kropfl, &
32 Julesz, 1982; Jonides, Irwin, & Yantis, 1982; Wolf, Hauske, & Lupp, 1978, 1980). Despite
33 the intuitive appeal of “spatiotopic fusion” (Irwin, 1992a) or the “integrative visual buffer”
34 account of transsaccadic integration (McConkie & Rayner, 1976), substantial empirical
35 evidence has shown it to be incorrect (e.g., Bridgeman & Mayer, 1983; Irwin, Brown, & Sun,
36 1988; Irwin, Yantis, Jonides, 1983; Irwin, Zacks, & Brown, 1990; O'Regan & Lévy-Schoen,
37 1983; Rayner & Pollatsek, 1983). According to an alternative account visual detail is lost
38 across a saccade; instead, visual information integration is carried out on a relatively abstract
39 level with visual form being represented in terms of structural or relational aspects of the
40 stimulus and its components (e.g., Carlson-Radvansky & Irwin, 1995; McConkie & Zola,
41 1979; Pollatsek Rayner, & Collins, 1984; Rayner, McConkie, & Zola, 1980). Consistent with
42 this view, maintenance of spatial position is relatively poor (e.g., Bridgeman, Hendry, &
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3 Stark, 1975; Bridgeman & Stark, 1979; Li & Matin, 1990a, 1990b; Mack, 1970; Pollatsek,
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5 Rayner, & Henderson, 1990; Stark, Kong, Schwartz, Hendry, & Bridgeman, 1976; Verfaillie,
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7 1997; Verfaillie & De Graef, 2000; Verfaillie, De Troy, & Van Rensbergen, 1994; Wallach &
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9 Lewis, 1966), while relational information is integrated quite accurately (Carlson-Radvansky,
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11 1999; Germeys, De Graef, Panis, Van Eccelpoel, & Verfaillie, 2004; Verfaillie, 1997).

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15 A similar conclusion was reached by Irwin (1991). Using a dot-matrix comparison
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17 task, Irwin showed that displacements of an entire dot pattern during an eye movement did
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19 not affect performance in detecting a change within the pattern. This suggests that visual
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21 information about the dot matrix is retained in a representation independent of absolute spatial
22
23 position, while preserving information about the relative position of elements within the
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25 pattern. In the same study, Irwin also investigated the time course of information decay in
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27 transsaccadic memory. Varying the temporal interval that separated the two patterns from 1
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29 ms to 5,000 ms had little effect on accuracy, suggesting that information in transsaccadic
30
31 memory is long lasting. Further research has provided evidence that transsaccadic memory is
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33 capacity limited, that is, only a few items seem to survive the saccade (Irwin, 1991, 1992a,
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35 1993, 1996; Irwin & Andrews, 1996). For example, using a partial-report procedure, Irwin
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37 (1992a) showed that only three to four letters in a multi-letter array could be retained across
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39 an eye movement, regardless of the number of letters presented presaccadically. Furthermore,
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41 report of letters near the saccade target was much more accurate than report of other letters in
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43 the array. Following up on this observation, Irwin and Gordon (1998) showed that attention
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45 determines what information is encoded into transsaccadic memory. Because attention
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47 automatically precedes an eye movement to the saccade target location, information near the
48
49 saccade target is more likely to be encoded (Deubel & Schneider, 1996; Hoffman &
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51 Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Shepherd, Findlay, &
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53 Hockey, 1986). In summary, a considerable body of evidence supports the idea that
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3 transsaccadic integration does not involve a global and visually detailed memory
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5 representation of the entire visual field, but rather a capacity-limited, attention-dependent,
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7 abstract representation, which is not strictly tied to spatial position and is relatively long
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9 lasting. What memory store could underlie the transsaccadic retention of this type of
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11 representation?
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15 To answer this question, it is useful to examine in what way transsaccadic memory
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17 differs from visual memory within fixations. There is general agreement for the existence of
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19 three main forms of visual memory (apart from short-term conceptual memory and long-term
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21 memory) within fixations: sensory or visible persistence, informational or schematic
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23 persistence, and visual short-term memory (Coltheart, 1980; Di Lollo & Dixon, 1988; Irwin,
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25 1992b; Irwin & Yeomans, 1986). The first form, visible persistence, is a phenomenal trace of
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27 the extinguished stimulus and is believed to be a mere by-product of residual activity in the
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29 visual pathway (Coltheart, 1980). Visible persistence decreases with increasing stimulus
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31 durations (known as the inverse duration effect), being negligible for stimulus exposures
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33 exceeding 100 ms (Di Lollo & Dixon, 1988, 1992; Dixon & Di Lollo, 1994). In other words,
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35 its decay is triggered by the onset of the inducing stimulus (see Figure 1). The second form of
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37 visual memory, informational persistence, is a non-visible, maskable representation (also
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39 called the visual analog) that is precategorical and capable of coding form and location in a
40
41 precise way. Its duration, estimated as ranging between 300 and 500 ms, is independent of
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43 stimulus exposure. In contrast to visible persistence, the visual analog representation starts to
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45 decay following stimulus offset (see Figure 1). Keysers, Xiao, Foldiak, and Perrett (2005)
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47 report an interesting study on the possible neurophysiological mechanisms underlying the
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49 visual analog. The third type of memory, visual short-term memory, is a non-maskable,
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51 postcategorical memory system, which has a limited capacity and a long duration. It holds an
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53 abstract and schematic representation with little detail. There is a remarkable resemblance
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between those characteristics and the kind of representation that seems to be carried across saccades: a capacity-limited, attention-dependent, relatively long lasting, abstract representation. This led Irwin (1991; also see Carlson-Radvansky & Irwin, 1995) to suggest that transsaccadic memory may in fact be the same as, or at least rely in large part on VSTM.

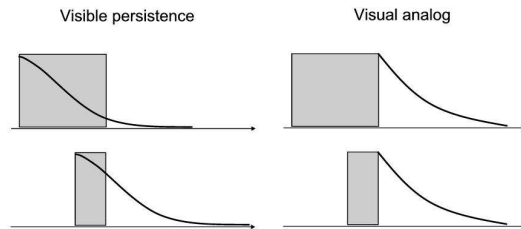


Figure 1. Schematic illustration of the time course of decay of visible persistence and the visual analog representation with long (top) versus short (bottom) stimulus presentations.

However, while spatiotopic visible persistence across saccades has been ruled out (e.g., Irwin, 1991; Irwin, et al., 1983, 1990; Jonides, Irwin, & Yantis, 1983; Rayner & Pollatsek, 1983), there is still no definite answer as to whether informational persistence across saccades does or does not exist and whether it can play a role (in addition to VSTM) in transsaccadic integration. The duration of informational persistence, which is well above the average saccade duration (approximately 40-50 ms), would certainly allow it. A number of observations indeed indirectly suggest that, under some conditions, informational persistence may operate across saccades.

First, it has been shown that detailed information regarding position and form in principle can be maintained transsaccadically (e.g., Hayhoe, Lachter, & Feldman, 1991; Lachter & Hayhoe, 1995; Melcher, 2005; Palmer & Ames, 1992). For example, Demeyer, De Graef, Wagemans, & Verfaillie (2009) showed that a presaccadic preview of an object facilitates its postsaccadic identification, even in a task in which participants have to discriminate between visually highly similar artificial shapes. Second, in a transsaccadic

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3 partial report task with letter arrays, Irwin (1992a) reported evidence for spatiotopic masking
4 when a mask-probe (instead of the typical bar-probe) was presented for a short period of time
5 following the saccade. Similarly, McRae, Butler, and Popiel (1987) found evidence for
6 spatiotopic masking in a full-report letter identification task. This suggests that certain
7 information retained across a saccade is volatile (susceptible to masking), in contrast to
8 information stored in VSTM. A third line of research supporting detailed transsaccadic
9 representations concerns the transsaccadic blanking effect (Deubel, Bridgeman, & Schneider,
10 1998, 2004; Deubel, Koch, & Bridgeman, 2010; Deubel, Schneider, & Bridgeman, 1996,
11 2002; Gysen, Verfaillie, & De Graef, 2002; also see Demeyer, De Graef, Wagemans, &
12 Verfaillie, 2010). In the blanking paradigm the saccade target is absent during the saccade and
13 for a short period (50 to 300 ms) at the beginning of the postsaccadic fixation. Under these
14 conditions, detection of intrasaccadic displacements improves drastically compared to the
15 situation without blanking. In other words, in the direct absence of a localized stimulus
16 following the end of a saccade, the visual system regains access to detailed position
17 information. A similar result was obtained in an experiment with form changes of
18 checkerboard-like stimuli (Deubel et al., 2002). Together, these findings imply that precise
19 information about the presaccadic target object is retained in transsaccadic memory but that
20 postsaccadic visual information affects its use.
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45 Consistent with these results, De Graef and Verfaillie (2002) provided evidence for
46 improved discrimination of transsaccadic in-depth orientation changes of saccade target
47 objects embedded within scenes when the postsaccadic image was blanked for a short period
48 of time. De Graef and Verfaillie (2002) interpreted the blanking effect as evidence for a
49 transsaccadic visual analog representation, that is, a high-capacity, non-selective, maskable
50 representation of the form and location of objects, which decays within approximately 300 ms
51 following stimulus offset. Blanking first of all postpones the presaccadic visual analog
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3 representation of a scene from being masked or overwritten by postsaccadic information.
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5 Second, attending a specific region of space following the saccade allows information within
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7 the visual analog to be selectively insulated against decay and masking by transferring it to a
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9 more durable store such as VSTM (Gegenfurtner & Sperling, 1993).
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13 To summarize, while a lot of research suggests that transsaccadic integration is
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15 supported by a relatively abstract and capacity-limited memory store (presumably VSTM),
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17 some findings show that more detailed location and form information can be remembered
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19 across a saccade than could be expected based on the characteristics of VSTM, possibly
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21 indicating a role for the visual analog representation. The main goal of the present study was
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23 to further assess whether transsaccadic memory is restricted to representations held in VSTM
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25 or whether it also contains a visual analog representation. In Experiment 1, we first examine
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27 information integration within fixations, trying to disentangle the contribution of VSTM, the
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29 visual analog representation, and visible persistence to change detection performance. Based
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31 on a better understanding of these components, we then investigate information integration
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33 across eye movements (Experiments 2 to 5).
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39 Integration of information across temporal gaps (e.g., the temporary disappearance of
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41 a stimulus during fixation, or a saccadic eye movement) requires the encoding of a stimulus,
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43 maintaining a representation in one or more memory stores for some time, and subsequently
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45 combining the memory trace with new information (e.g., Brockmole & Irwin, 2005;
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47 Brockmole & Wang, 2003; Henderson & Hollingworth, 2003; Hollingworth, 2004). During
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49 each of these processes, information can get lost, causing incomplete integration (e.g., see
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51 Rensink, 2002; Simons & Rensink, 2005, for reviews of the extensive literature on blindness
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53 for changes, not only across saccades, but also across other temporal gaps). In the present
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55 experiments, integration is assessed by means of a change detection paradigm. All reported
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57 experiments involved the presentation of a circular array of letters or line drawings of
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3 everyday objects, for a short period of time. After a brief temporal interstimulus interval of
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5 variable duration, a second array was presented containing a single letter (or object) at one of
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7 the places on the circular array and participants had decide as to whether the letter object in
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9 that location had changed across the temporal gap. Correct detection of a change or the
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11 absence of change implies (1) that a representation of the initial stimulus is maintained across
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13 the temporal gap and (2) that the participant is able to compare this representation with a
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15 subsequent stimulus. Note that the first requirement, namely the existence of a representation
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17 of the initial stimulus, is a necessary but not a sufficient condition for the detection of
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19 changes; the complete absence of a representation cannot be directly inferred from a failure to
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21 detect a change.
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26 27 Experiment 1

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29 The purpose of Experiment 1 was threefold. In the first condition, we investigated the
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31 time course of information decay in VSTM by examining performance in the detection of
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33 changes in character displays as a function of interstimulus interval (ISI). Participants were
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35 shown a sequence of two displays separated by a blank ISI of variable duration (50, 100, 150,
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37 200, 250, 300, 450, 700, or 1000 ms). The first display (memory display) consisted of eight
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39 letters arranged in a circular pattern and was presented for 250 ms. The second display (test
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41 display) contained only one letter and remained present until a response was made. In 50% of
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43 the trials the single letter matched the corresponding letter in the memory display, in the
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45 remaining 50% the test letter differed from the corresponding letter in the memory display.
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47 The participant's task was to indicate whether the letter in the test display was the same as, or
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49 differed from the letter in the same position in the memory display. Previous studies (e.g.,
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51 Irwin, 1991; Pashler, 1988; Phillips, 1974) using a similar procedure reported excellent
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53 change detection performance at very short ISIs. At longer ISIs however, performance
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55 dropped but remained stable with increasing ISIs. These results were interpreted as evidence
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3 for two kinds of visual memory within fixations: a rapidly decaying, high-capacity sensory
4 memory that supports apparent motion (at the very short ISIs) and a slowly decaying, limited-
5 capacity VSTM. In the present experiment, we were mainly interested in the time course of
6 information decay within VSTM.
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12 The second objective in Experiment 1 was to assess the amount of information that is
13 still available after stimulus offset of the memory display. Becker, Pashler, and Anstis (2000)
14 provided evidence that more information is represented in the visual system than change
15 detection experiments (as our first condition) might reveal. They showed that cueing the
16 location of a possible change during the blank ISI significantly improved change detection.
17 As Becker et al. (2000) point out, this finding is not surprising in light of the iconic-memory
18 literature. Partial-report experiments have consistently shown that an iconic memory trace can
19 last for several hundreds of milliseconds after stimulus offset and that it can be read out by
20 selective attention. We will assume that two main types of information are still available:
21 information stored in VSTM (as assessed in the first condition) and information in iconic
22 memory. Participants were shown an initial array of eight letters for 250 ms, directly followed
23 by a 50 ms duration cue. The cue indicated the future location at which a change could take
24 place. The time between the initial display and test display (ISI) was manipulated as in the
25 first condition.
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45 Third, we examined the time course of decay of the visual analog: In the third
46 condition, following offset of the initial display. ISI was held constant (1000 ms), while a cue,
47 indicating the future location of a possible change, was presented at different moments
48 following the offset of the memory display (0, 50, 100, 150, 200, 250, 300, or 400 ms).
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57 Method

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3 Participants. Three University of Leuven students participated in Experiment 1. They
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5 were paid 7.5 Euro for each hour of participation. All participants had normal or corrected-to-
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7 normal vision.
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10 Stimuli. As shown in Figure 2, the stimulus display in each of the three conditions
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12 consisted of eight letters arranged in a circular pattern. Letters in the array were shown in
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14 uppercase Ariel font and subtended 1° vertically. The letters were centred 4° from the center
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16 of the circular pattern and were equally spaced. To avoid afterimages due to phosphor
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18 persistence, we displayed the letters black (pixels off, 0.19 candela/m^2) on white (pixels on,
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20 $13.90 \text{ candela/m}^2$). For each trial, the letters in the initial (memory) display were selected
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22 randomly from a set of sixteen letters (B, C, D, F, G, H, K, L, M, N, P, R, S, T, V, and Z),
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24 subject to the constraint that no letter appeared more than once. The second (test) display
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26 contained only one letter (at one of the positions occupied by the letters in the memory
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28 display). In 50% of the trials, this test letter was identical to the corresponding letter in the
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30 memory display. In the remaining 50% of the trials, one letter in the memory array was
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32 substituted for a letter that was not present in the memory display.
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38 Apparatus. The stimuli were displayed in 60-Hz mode on a Sony GDM-W900
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40 Trinitron Color Graphic Display with a 756×486 resolution, which subtended $17^\circ \times 11^\circ$. Eye
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42 movements were recorded with a Generation 5.5 dual-Purkinje-image eye tracker (Crane &
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44 Steele, 1985). This system has an accuracy of 1 min of arc and a 1000-Hz sampling rate. It
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46 was interfaced with a PC, storing every sample of the left eye's position. For each sample, the
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48 computer made an on-line decision about the eye state: fixation, saccade, blink, or signal loss.
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50 This on-line classification algorithm enables detection of a saccade within 4 ms of the onset
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52 of the saccade. Eye state and position were fed into a second PC in control of stimulus
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54 presentation. Display changes were accomplished within 16.7 ms because they could be
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initiated at any moment during the screen refresh cycle (the display-change command did not wait for the vertical blank).

Procedure. Participants were seated at 150 cm from the stimulus display, with their head stabilized by a head rest and a bite bar with dental impression compound. Once the eye tracker was successfully calibrated for nine points along the diagonals of the stimulus field, a block of practice trials was initiated followed by an experimental session.

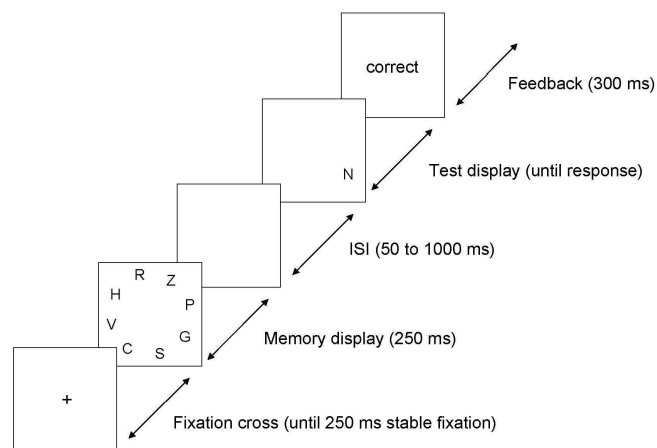


Figure 2. Schematic illustration of events and time course of a trial in the no-cue condition in Experiment 1.

The events and time course of the three trial types are schematically illustrated in Figure 3. A trial in the first condition (the *no-cue* condition) consisted of the following events (also shown in Figure 2). First, a fixation cross appeared in the center of the display. Participants were instructed to fixate the cross, and calibration accuracy was checked. Once a 250-ms stable fixation was detected on the fixation cross (i.e., a stable fixation within an invisible square of $0.5^\circ \times 0.5^\circ$ enveloping the fixation cross), it disappeared and the initial letter array was displayed for 250 ms. If at any moment during the presentation of this

memory display, participants made an eye movement that carried the eyes outside the invisible $0.5^\circ \times 0.5^\circ$ square, the trial was interrupted, followed by the beginning of a new trial (less than 1% of the trials). Then, following a blank ISI of 50, 100, 150, 200, 250, 300, 450, 700, or 1000 ms, the test display appeared that contained one letter (either the same as the corresponding letter in the memory display or different from it). The test display remained on screen until the participant pressed one of two response buttons indicating a same or different response. Once the response was recorded, a feedback message was displayed in the center of the screen for 300 ms (*correct* or *wrong*) followed by the beginning of a new trial after an interval of 1,500 ms.

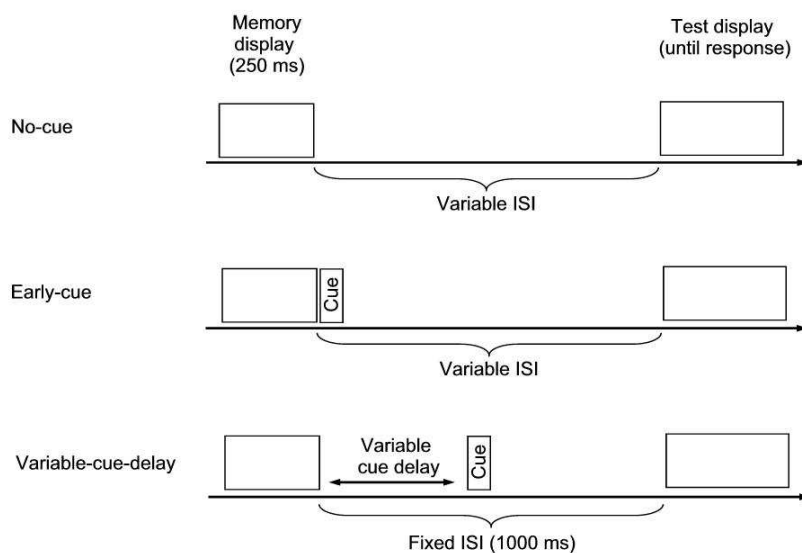


Figure 3. Schematic illustration of events and time course in the no-cue, early-cue, and variable-cue-delay trials of Experiment 1.

The course of a trial in the second condition (the *early-cue* condition) was identical, except that, following the offset of the memory display, a cue was presented for 50 ms during the ISI. The cue was a red radial line segment, 3° in extent, pointing from the centre of the

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3 array to a location previously occupied by a letter. Participants were informed that the probed
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5 letter in the test display would always be at the cued location.
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8 The third condition (the *variable-cue-delay* trials) differed from the previous two
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10 conditions in two respects. First, the ISI between the memory array and the test array was held
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12 constant at 1000 ms. Second, the timing of the 50 ms duration cue within the ISI was
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14 manipulated. The cue was presented 0, 50, 100, 150, 200, 250, 300, 400, 650, or 950 ms
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16 following the offset of the memory display.
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20 Design. Each participant carried out one practice block of 90 trials and 36
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22 experimental blocks of 108 trials. In total, each participant completed 3888 trials, that were a
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24 factorial combination of the three types of trials (no-cue, early-cue, and variable-cue-delay), 9
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26 timings (ISIs of 50, 100, 150, 200, 250, 300, 450, 700, and 1000 ms for the first two types of
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28 trials, and cue delays of 0, 50, 100, 150, 200, 250, 400, 650, and 950 ms for the third type of
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30 trials), 8 possible letter change positions, 2 change conditions (same or different), and 9
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32 repetitions. This resulted in 144 observations for each trial type x timing combination. Each
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34 block of 108 trials consisted of a factorial combination of 3 types of trials, 9 timings, and 2
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36 change conditions with an equal distribution of the position of a possible letter change. The
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38 experiment was completed in 6 sessions that each lasted approximately 1.5 hr.
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43 Results and Discussion

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45 Figure 4 shows the percentage correct change detection as a function of timing and
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47 trial type. Separate repeated measures analyses of variance (ANOVA) were carried out for
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49 each trial type with the timing variable as a within-subject variable.
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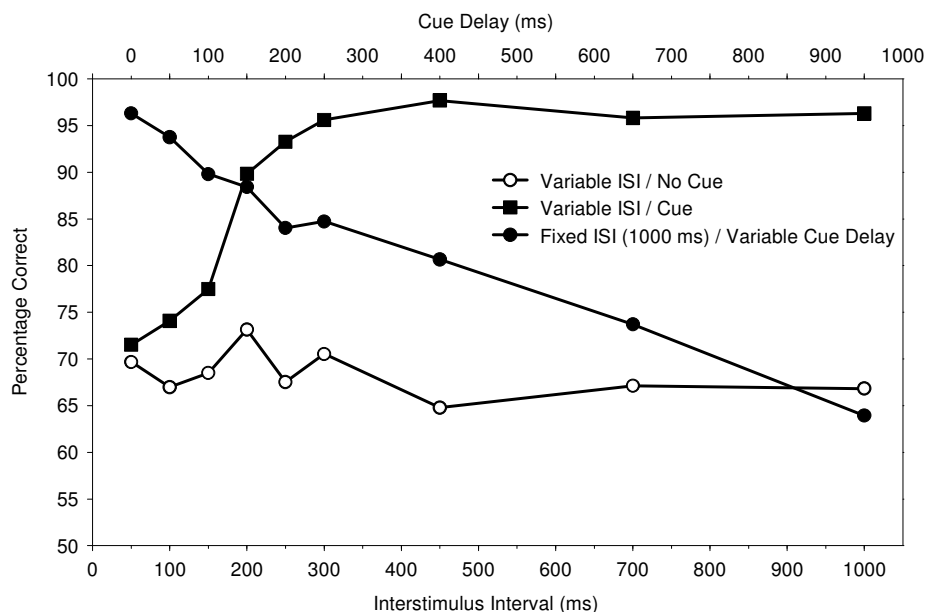


Figure 4. Percentage correct detection in Experiment 1 as a function of interstimulus interval (for the variable ISI / no cue and variable ISI / cue conditions) or cue delay (for the fixed ISI / variable cue delay condition).

Although performance in the *no-cue* condition seemed to drop slightly with increasing ISI, the effect of ISI was not reliable, $F(8, 16) = 1.44$, $p = .25$, $MSE = .0013$. The present results are very similar to those observed by Pashler (1988) and others (e.g., Irwin, 1991; Luck & Vogel, 1997; Phillips, 1974). Indeed, performance did not deteriorate significantly across the entire range of ISIs reflecting the well-established property of VSTM: a relatively durable, though capacity-limited store (e.g., Irwin, 1991). (Note that, contrary to the previously mentioned studies, we did not observe a peak in performance at the very shortest ISI (50 ms). However, the absence of such peak in the present experiment is not completely at odds with previous work. The sensory storage effect, as referred to by Irwin (1991), has been shown to decay rapidly. For example, Pashler (1988) reported the presence of the effect at an ISI of 34 ms, while it was gone at 67 ms. In a similar study, Becker, Pashler, and Anstis

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3 (2000) reported no increase, even with ISIs as short as 16 ms. Hence, it seems that in
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6 Experiment 1, the rapidly decaying sensory storage is unusable at an ISI of 50 ms.)

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8 For the *early-cue* condition, the effect of ISI proved reliable, $F(8, 16) = 43.10$, $p <$
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10 $.0001$, $MSE = .0008$. Performance was lowest at ISI 50 ms but increased with longer ISIs. At
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12 an ISI of 300 ms performance reached ceiling and remained stable thereafter. Our main
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14 objective in Experiment 2 was to assess the amount of information that is still available after
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16 stimulus offset of the initial display. The very accurate performance at longer ISIs (> 200 ms)
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18 clearly indicates that a relatively good representation of all letters presented in the memory
19
20 display was still present after stimulus offset. Comparison with the results obtained in the no-
21
22 cue condition suggests that the increased performance in the early-cue condition, especially at
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24 longer ISIs, reflects the additional use of iconic information by a selective transfer process.
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26 There are two aspects of the present data that deserve further discussion. First, change
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28 detection performance did not reach ceiling right away, but gradually increased with ISIs in
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30 the 50 to 300 ms range. The most obvious explanation for this effect is that it takes a certain
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32 amount of time to read out and transfer the cued item from iconic memory to a more durable
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34 store. This explanation assumes that read-out and transfer from iconic memory is disrupted
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36 once the test display appears. Second, performance did not decline with increasing ISI once
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38 ceiling performance was obtained (ISIs 300 to 1000 ms), indicating durable storage of the
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40 cued item, probably in VSTM. In sum, more information seems to be represented after
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42 stimulus offset of the memory display than is usually revealed by classical change detection
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44 experiments. Indeed, cueing the location of a possible change immediately following offset of
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46 the initial display enhances the ability to detect changes. This is consistent with Becker et al.
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48 (2000) and earlier reports (e.g., Averbach & Coriell, 1961; Di Lollo & Dixon, 1988;
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50 Gegenfurtner & Sperling, 1993; Sperling, 1960). We interpret these findings as evidence for a
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52 visual analog representation following stimulus offset. The increase in detection performance
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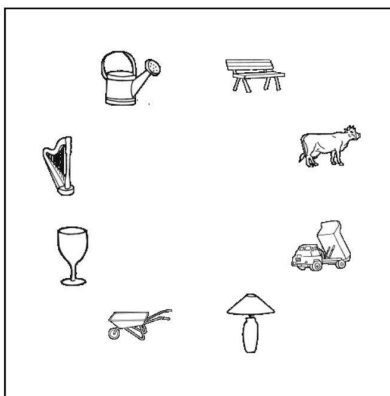
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3 with increasing ISI duration is assumed to be caused by a selective read-out and transfer
4 process of a representation of the cued item in the visual analog to a durable memory store
5 (VSTM). This process takes a certain amount of time and is interrupted whenever a new
6 stimulus is presented.
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12 In the condition with a fixed ISI of 1000 ms but with a *variable cue delay*, a
13 significant effect of cue delay on detection performance was obtained, $F(8, 16) = 20.61$, $p <$
14 $.0001$, $MSE = .0015$. Performance was near-perfect (96%) when the cue was presented
15 immediately following the offset of the memory display and declined with increasing cue
16 delays. It was only at the longest cue delays that change detection performance declined to the
17 level of performance in the no-cue condition. These results confirm the existence of a visual
18 analog representation, which starts to decay following stimulus offset.
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29 In summary, change detection performance is partly based on a capacity limited and
30 durable memory representation, traditionally referred to as VSTM. Second, evidence for a
31 non-selective, maskable, and relatively fast decaying representation was observed. Following
32 Di Lollo and Dixon (1988), this representation is referred to as the visual analog. We have
33 shown that selectively attending a cued location enables read-out and transfer of item
34 information from the visual analog to VSTM, where it can be stored for subsequent
35 comparison with items in the test display. However, read-out from the visual analog and
36 transfer to VSTM is time consuming, requires focused attention, and is interrupted by the
37 appearance of new information or is no longer possible when decay of the visual analog
38 representation has reached the point where it cannot be read out properly. When read-out from
39 the visual analog fails, change detection will be determined by the presence or absence of a
40 representation of that item in VSTM. Note that in the latter case, the VSTM representation is
41 created during presentation of the test display, whereas in the first, the VSTM representation
42 is created after presentation of the cue, that is, following read-out of the visual analog.
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3 Recently, Sligte, Scholte, and Lamme (2008; also see Sligte, Scholte, & Lamme,
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6 2009) reported similar effects. They interpret their findings as evidence for a fragile form of
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8 VSTM (apart from traditional VSTM), instead of a visual analog representation. However, we
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10 will argue that the main findings presented in the present study are well captured by
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12 characteristics attributed to the visual analog.
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15 We would like to add two notes. First, in Experiment 1, all types of trials (no-cue,
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17 early-cue, and variable-cue-delay) were presented in random order to all participants.
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19 Although there is no a priori reason to expect that this would have an effect, we ran three
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21 separate experiments (with three independent, naïve groups of participants, ranging from 4 to
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23 6 subjects) corresponding to the three main conditions of Experiment 1. We replicated the
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25 findings of Experiment 1. Second, one could claim that letters are overlearned visual stimuli
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27 and that generalization of the present findings to vision of more complex objects is
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29 unwarranted. We therefore repeated Experiment 1 with line drawings of everyday objects
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31 (obtained from van Diepen & De Graef, 1994). An example of a memory display is shown in
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33 Figure 5. The findings of Experiment 1 were replicated.
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53 *Figure 5.* Example of a memory display in a replication of Experiment 1 with line drawings of
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55 objects instead of letters as stimuli.
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3 Now that we have established the properties and the role of both VSTM and the visual
4 analog in a within-fixation change detection paradigm, we return to the main topic of the
5 present article, that is, transsaccadic memory. As outlined in the introduction, our main goal is
6 to assess whether transsaccadic memory is restricted to representations held in VSTM or
7 whether it also contains a visual analog representation. Experiments 2-5 examined
8 performance in the detection of changes across eye movements. Similarly to the within-
9 fixation Experiment 1, displays consisted of eight letters (or line drawings of everyday
10 objects) presented in a circular pattern. During the initial memory display, participants were
11 fixating the center of the array. Apart from the 8 objects, the initial display contained a line
12 segment pointing to one of the objects. Participants were instructed to make an eye movement
13 to this object as rapidly as possible. During this saccade, the memory display was erased and a
14 postsaccadic image was presented. Depending on the specific conditions, the test display was
15 presented either directly following the saccade or postponed for a brief period of time
16 (blinking). In the latter conditions, a cue indicating the location of the to be probed item was
17 inserted at different moments during the blank interval. As in Experiment 1, the test display
18 contained a single item and remained on screen until the participant pressed one of two
19 response buttons indicating a same or different response.

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22 To study the question whether transsaccadic memory includes a visual analog
23 representation, we first need to set out what kind of evidence would allow for such a
24 conclusion. First, to date, blanking effects have only been observed for the saccade target
25 object or objects in the vicinity of the saccade target. In other words, blanking effects have
26 only been observed for entities that most probably received focused attention prior to the
27 saccade. A blanking effect for items that were not attended before the saccade, however,
28 would constitute more convincing evidence for a transsaccadic visual analog representation.
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30 Second, read-out and transfer of a specific item from the visual analog to VSTM requires

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3 selective attention. This implies that blanking in itself should not be sufficient to regain
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5 additional and/or more detailed information. In other words, delaying the postsaccadic
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7 reafference of a stimulus without at the same time redirecting attention to the location where
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9 information has to be read out from the visual analog should not improve change detection
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11 performance. Third, information within the visual analog is subject to decay. This implies that
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13 delaying the redirection of attention to a specific location in the visual field during the
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15 blanking interval should decrease the likelihood that an item can be read out from the visual
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17 analog. Fourth, while VSTM holds a non-maskable representation, read-out from the visual
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19 analog representation can be interrupted by a mask. This implies that the presentation of a
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21 masking cue at the to be probed item location during a blanking interval should not affect
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23 change detection performance if detection were purely based on a VSTM representation. If on
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25 the other hand, the presentation of a localised mask instead of a normal cue causes a decrease
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27 in performance, then selective read-out from a visual analog may be prevented. Finally, if
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29 selective read-out from the visual analog is responsible for the blanking effect, than read-out
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31 and transfer of information should show the same properties as in the fixation experiment.
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33 That is, read-out and transfer to VSTM should be relatively slow and interrupted whenever a
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35 new stimulus appears in the visual field. In the following experiments (Experiments 2-5), we
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37 will examine each of these points in detail.
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45 46 Experiment 2

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48 Experiment 2 included four conditions, one in which the test display was present
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50 immediately following the critical saccade from the center of the display to one of the items in
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52 the memory display (no-blank condition) and three in which the display was blanked for 950
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54 ms followed by the test display (see Figure 6). The first blanking condition contained no cue
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56 during the blanking interval (blank / no-cue condition), while the second and third contained a
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58 small red disk for 50 ms, indicating the location at which the probe item in the test display
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would appear. The cue could either appear 50 ms into the blanking interval (blank / early-cue condition) or 450 ms into the blanking interval (blank / late-cue condition).

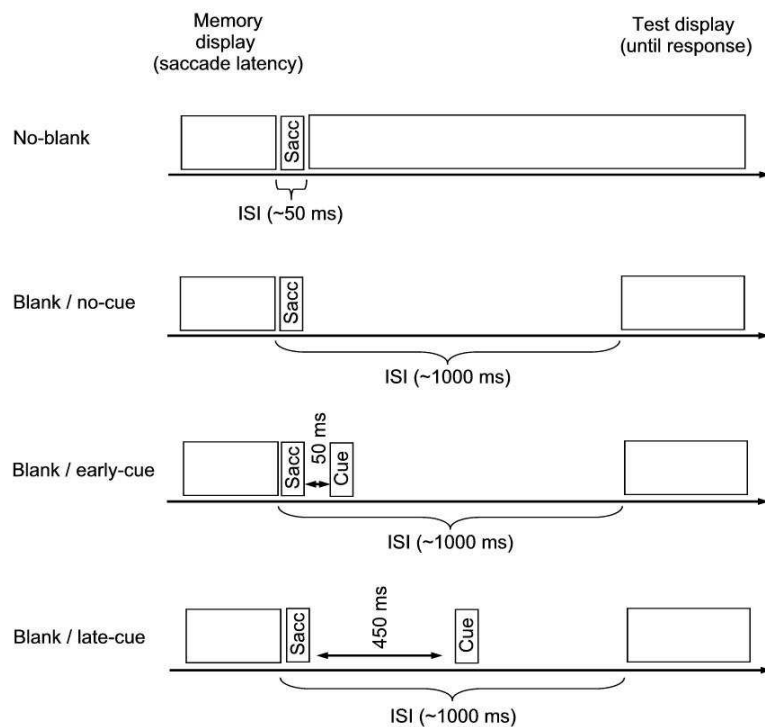


Figure 6. Schematic illustration of events and time course in the no-blank, blank / no-cue, blank / early-cue, and blank / late-cue trials of Experiment 2 (Sacc = saccade).

The no-blank condition served as a baseline to which the effects of blanking without cue and blanking in combination with cueing could be assessed. If the blanking effect observed in previous studies is due to read-out from a transsaccadic visual analog representation, we predicted performance in the blank / early-cue condition (and possibly to some degree in the blank / late-cue condition, depending on the decay function of the visual analog) to be better than in the no-blank condition.

In all conditions, we expected change detection performance to be best for items presented at or near the saccade target location. Because attention precedes eye movements

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3 (e.g., Deubel & Schneider, 1996; Kowler et al., 1995; Hoffman & Subramaniam, 1995),
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5 objects at these locations are preferentially coded in VSTM (e.g., Irwin & Gordon, 1998;
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7 Schneider, 1999). However, if a blanking effect is observed, we are specifically interested to
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9 see whether this effect is restricted to items in the saccade target region or whether detection
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11 at locations more distant from the saccade target also improves. Under the assumption of a
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13 non-selective visual analog representation, blanking effects should not be limited to items at
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15 or near the saccade target location.
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19 Method

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22 Participants. Two paid University of Leuven students and the first author participated
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24 in Experiment 2. All participants reported normal vision.
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27 Stimuli and apparatus. The stimuli and apparatus were identical to those used in
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29 Experiment 1. Transsaccadic display changes were typically achieved within 21 ms. Saccades
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31 were detected within 4 ms of the onset of the saccade by an on-line classification algorithm.
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33 Subsequent display changes were accomplished within 16.7 ms because they could be
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35 initiated at any moment during the screen refresh cycle (the display-change command did not
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37 wait for the vertical blank).
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41 Procedure. Each trial consisted of the following events. First, a fixation cross appeared
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43 in the centre of the display. Participants were instructed to fixate the cross and calibration
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45 accuracy was checked. Once a 250 ms stable fixation was detected on the fixation cross (i.e.,
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47 a stable fixation within an invisible square of $0.5^\circ \times 0.5^\circ$ enveloping the fixation cross), it
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49 disappeared and the presaccadic letter array was displayed. In addition to the circular array of
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51 letters, the initial display contained a cue that indicated the letter to which a saccadic eye
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53 movement had to be made. The cue was a radial line segment, 2.5° in extent, pointing from
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55 the centre of the array to a location occupied by one of the letters. Participants were instructed
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57 to saccade as rapidly as possible to the letter once the initial display was presented. If an eye
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3 movement was not initiated within 400 ms following onset of the memory display, the trial
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5 was interrupted and the viewer was warned to make more timely saccades. Contingent upon
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7 the detection of a saccade leaving the center of the screen, a change to a postsaccadic display
8
9 was made intrasaccadically. If the saccade to the previously indicated letter did not land
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11 within an invisible square of $2^\circ \times 2^\circ$ enveloping the presaccadic letter, and this within 100 ms
12
13 after saccade onset, the trial was interrupted and the viewer was warned to make more
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15 accurate saccades. From the moment the eyes had landed within the specified region,
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17 participants were free to move their eyes anywhere within the display.
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22 The four conditions differed from each other in the events that occurred after the
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24 saccade (Figure 6). In the no-blank condition, the test-display was present directly following
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26 the eye movement. In the blank / no-cue condition, a blank field was presented for 950 ms
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28 after saccade landing, followed by the test display. The same was true for the blank / early-
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30 cue and late-cue conditions, except that a cue was presented for 50 ms during the 950 ms
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32 blanking interval. The cue was a red disk $.25^\circ$ in diameter. It was presented centered on a
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34 location previously occupied by one of the letters. In the blank / early-cue condition, the cue
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36 appeared after 50 ms of the blanking interval (i.e., 50 ms blank / 50 ms cue / 850 ms blank), in
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38 the blank / late-cue condition the cue appeared after 450 ms (i.e., 450 ms blank / 50 ms cue /
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40 450 ms blank). The test display remained on screen until the participant pressed one of two
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42 response buttons indicating a same or different response. Once the response was recorded, a
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44 feedback message was displayed in the centre of the screen for 300 ms (*correct* or *wrong*)
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46 followed by the beginning of a new trial after an interval of 1,500 ms.
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53 Design. Each subject participated in three practice blocks and 16 experimental blocks
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55 of 128 trials. In total, each participant completed 2048 experimental trials that were a factorial
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57 combination of 4 conditions (no-blank, blank / early-cue, blank / late-cue, and blank / no-cue),
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59 8 saccade target locations, 8 possible letter change positions, 2 change conditions (same or
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3 different), and 4 repetitions. The experiment was completed in 5 sessions (one practice
4 session and four experimental sessions) that each lasted approximately 1 hr 15 min.
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7 Results & Discussion

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10 Trials that were interrupted (i.e., saccade latencies above 400 ms or spatially
11 inaccurate saccades) were excluded from subsequent analyses, as were trials with signal loss,
12 changes that did not occur intrasaccadically, or blinks occurring before the critical saccade to
13 the saccade target location. Of the trials, 10.5% were eliminated in total. Average duration of
14 the saccade from the center of the circular array to the indicated saccade target location was
15 57 ms (range 35-80 ms) measured from saccade onset to the end of the postsaccadic lens
16 overshoot (Deubel & Bridgeman, 1995; Van Rensbergen, De Troy, Cavegn, De Graef, van
17 Diepen, & Fias, 1993). Because saccade-contingent display changes took only 21 ms, they
18 were all completed well before the end of the saccade. Saccade latencies were 235 ms on
19 average.
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34 In this and subsequent experiments, we were specifically interested in two questions:
35 First, does blanking affect change detection performance and second, if so, is the blanking
36 effect limited to items at or near the saccade target object? To answer these questions, change
37 detection performance, expressed as the percentage correct responses, was analysed in a
38 repeated-measures ANOVA with trial type and relative probe position as within-subject
39 variables. As shown in Figure 7, relative probe position refers to the position of the probed
40 item relative to the saccade target and has five levels. If the probed item was the saccade
41 target object, relative probe position was set at 0, indicating no difference between probe and
42 saccade target location. If the probed item was in a location adjacent to the saccade target,
43 it was labelled 1 and so on, until level 4 which indicated that the probed item was in a location
44 opposite to the saccade target location.
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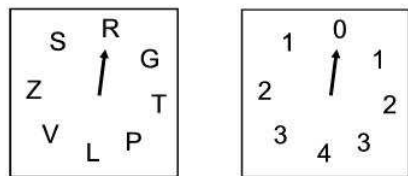


Figure 7. Assignment of relative probe position. Arrow indicates saccade direction.

The analysis revealed main effects of trial type, $F(3, 6) = 15.00$, $p < .004$, $MSE = .0028$, and relative probe position, $F(4, 8) = 174.96$, $p < .0001$, $MSE = .0020$. In addition, the interaction between trial type and relative probe position was significant, $F(12, 24) = 2.43$, $p < .04$, $MSE = .0014$. Figure 8 shows detection performance as a function of trial type and relative probe position. The interaction was largely due to a ceiling effect at relative probe position zero, regardless of trial type. In other words, detecting a change to the saccade target item was near-perfect and unaffected by trial type.

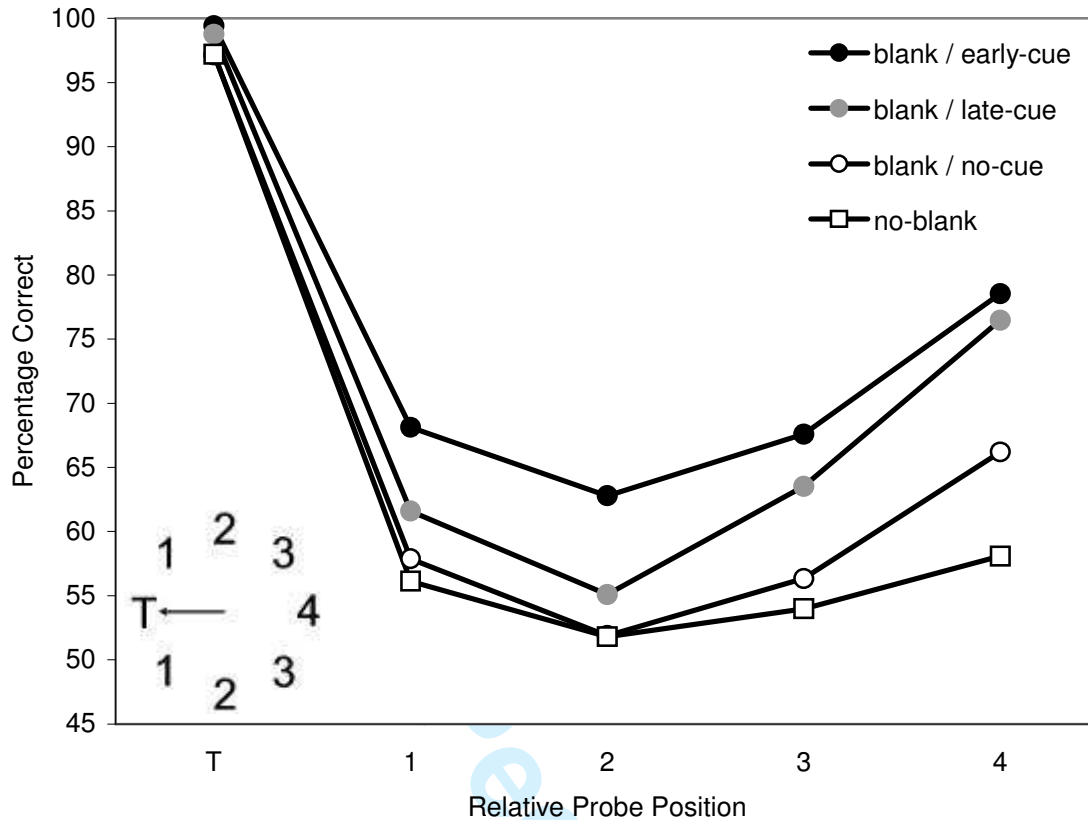


Figure 8. Percentage correct detection in Experiment 2 as a function of relative probe position (T = saccade target) and trial type.

Because of this ceiling effect, the data were reanalysed excluding trials in which the saccade target was probed. The main effects of trial type, $F(3, 6) = 14.49$, $p < .004$, $MSE = .0033$, and relative probe position, $F(3, 6) = 19.04$, $p < .002$, $MSE = .0022$, remained reliable. However, the interaction between the two factors disappeared, $F(9, 18) = 1.43$, $p = .25$, $MSE = .0016$. Change detection performance for non-saccade target items in the no-blank, blank / no-cue, blank / late-cue, and blank / early-cue conditions were 54.6%, 56.9%, 62.4%, and 67.9% respectively. Planned comparisons between the no-blank condition and blanking conditions revealed no significant blanking effect for the blank / no-cue condition, $F(1, 2) = 5.12$, $p = .15$, $MSE = .0011$, a marginal effect for the late-cue condition, $F(1, 2) = 10.77$, $p < .09$, $MSE = .0047$, and a significant effect for the early-cue condition, $F(1, 2) = 219.06$, $p <$

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3 .005, $MSE = .0006$. Quite surprisingly, change detection performance for non-saccade target
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5 items did not decline as a function of distance to the saccade target (i.e., best for items
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7 adjacent to, and worst for items contralateral to the saccade target). Instead, performance was
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9 worst when relative probe position was 2 (55.4%), somewhat better for positions 1 and 3
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11 (60.9% and 60.3%), and best for position 4 (69.8%). This is a data pattern that we replicated
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13 in Experiments 3-5. We will return to this observation in the General Discussion.
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17 The results obtained in the present experiment can be summarized as follows. First,
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19 under blanking and no-blanking conditions, detection of changes in the saccade target item
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21 across saccades was almost perfect and superior to detection performance of changes to other
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23 items. In addition, change detection was extremely poor for non-saccade target items (further
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25 referred to as bystander items) when the test display was presented immediately following the
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27 saccade. Under the assumption that focused attention is needed to store an item into VSTM,
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29 this seems to indicate that attention was almost entirely restricted to the saccade target during
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31 presentation of the memory display. A second observation is that blanking the postsaccadic
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33 display without presenting a cue did not improve detection performance. Instead, focused
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35 attention to the location of a to-be-probed item (by means of a cue) was needed to obtain a
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37 blanking effect (blank / cue conditions). Third, a blanking effect was observed for non-
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39 saccade target or bystander items. Fourth, the blanking effect for bystander items did not
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41 decline as a function of eccentricity from the saccade target. Finally, when attention was not
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43 immediately directed to the location of a to-be-probed item during the blanking interval
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45 (blank / late-cue condition), the blanking effect was strongly reduced. Together these results
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47 lend support to the hypothesis that transsaccadic memory includes more information than is
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49 observed under the usual no-blanking circumstances. The question whether this additional
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51 information is related to a transsaccadic visual analog representation remains hypothetical.
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53 However, the present results do show three properties that are to be expected if a visual
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3 analog representation were involved: A blanking effect is observed for items that are less
4 likely to be attended presaccadically (bystander items), focused attention is required to use
5 this representation for change detection (blank / no-cue vs. blank / early-cue), and the
6 representation shows signs of relatively fast decay (blank / early-cue vs. blank / late-cue).
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12 Note that analogously to the case of Experiment 1, we repeated Experiment 2 with line
13 drawings of everyday objects instead of letters as stimuli (see Figure 5 for an example). The
14 findings of Experiment 2 were replicated.
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19 Experiment 3

20 In Experiment 3, we further investigated the representational format that supports the
21 blanking effect as observed in the blank / early-cue conditions of Experiment 2. More
22 specifically, we investigated whether the transsaccadic representation that supports the
23 blanking effect is susceptible to spatiotopic masking. It is generally assumed that VSTM
24 holds a non-maskable representation and information can be accessed directly, while read-out
25 from the visual analog representation is maskable (e.g., Irwin, 1992b). This implies that the
26 presentation of a masking cue at the to-be-probed item location during a blanking interval
27 should not affect change detection performance if detection were purely based on a VSTM
28 representation. If, on the other hand, selective read-out from a visual analog is involved,
29 presenting a localised mask instead of a non-masking, normal cue should strongly affect
30 performance. In the latter case, the mask would prevent read-out from the visual analog,
31 presumably because it overwrites information within the visual analog.
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50 To assess whether the transsaccadic representation that supports the blanking effect is
51 susceptible to spatiotopic masking, two types of cues were used. The first cue was a small red
52 disk, identical to the cue used in Experiment 2. The second type of cue was a square box
53 presented in such a way that a letter would just fit within its contours. Although both types of
54 cues were presented at the spatial location of a presaccadically presented letter, we assumed
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3 that only the square cue would in principle be capable of masking the letter. The choice of this
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5 second type of cue was based on the results of partial report experiments conducted within
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7 fixations (e.g., Averbach & Coriell, 1961) and across saccades (Irwin, 1992a). For example,
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9 in a transsaccadic partial-report study by Irwin (1992a), both a traditional bar probe appearing
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11 above or below an array location and a square probe that overlapped spatially with the
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13 location of a letter was used. Irwin found a masking effect of the spatially overlapping probe
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15 when the interval between the memory display and the probe (which included the time of an
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17 eye movement) was 40 ms.
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22 The present experiment had three conditions in which the postsaccadic display was
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24 blanked for 950 ms and one condition without blanking. The first two blanking conditions
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26 contained a cue throughout the blanking interval (see Figure 9), either a small red disk (blank
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28 / constant-cue condition) or a square box (blank / constant-mask-cue condition). The third
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30 blanking condition, was identical to the blank / early-cue condition used in Experiment 2.
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32 Here, the cue was a small red disk that appeared 50 ms into the blanking interval and
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34 remained there for 50 ms. (We will stick to the term blank / early-cue condition even though
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36 in the present experiment the term ‘early’ is somewhat inappropriate when compared to the
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38 blanking conditions with a constant cue, because in these conditions the cue appears even
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40 earlier (50 ms).) Finally, a no-blank condition, identical to that in Experiment 2, was
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42 introduced to set a baseline to which blanking effects could be assessed. If the blanking effect
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44 is supported by a maskable visual analog representation, performance should be worse with
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46 the square-like cue than when the cue consisted of a small disk. In addition, the blank / early-
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48 cue condition and no-blank condition served as control conditions to assess blanking effects
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50 in the two blanking conditions with a constant cue.
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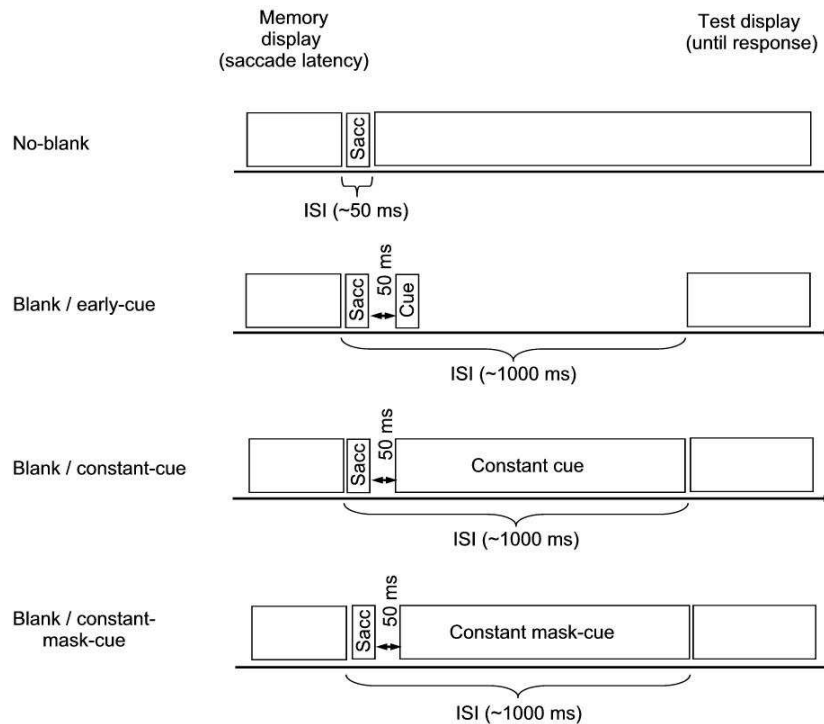


Figure 9. Schematic illustration of events and time course in the no-blank, blank / early-cue, blank / constant-cue, and blank / constant-mask-cue trials of Experiment 3 (Sacc = saccade).

Method

Participants. Two paid University of Leuven students and the first author participated in Experiment 3. All participants reported normal vision.

Procedure. The trial sequence prior to the critical saccade to the saccade target letter was identical to that in Experiment 2. Figure 10 shows the time course and events of a single trial for each of the four conditions. In the no blank / no cue condition, the test-display was present directly following the eye movement. In the blanking conditions, a blank field was presented for 950 ms after saccade landing followed by the test display. In the blank / constant-cue and blank / constant-mask-cue conditions, a cue was present throughout the blanking interval. In the blank / early-cue condition, the cue appeared after 50 ms of the blanking interval and remained on screen for only 50 ms (i.e., 50 ms blank / 50 ms cue / 850

ms blank). In the blank / constant cue and the blank / early-cue conditions, the cue was a red disk .25° in diameter presented centered on a location previously occupied by one of the letters. In the blank / constant-mask-cue condition the cue was a transparent box that measured 1.25° by 1.25°. Figure 10 illustrates the size of the box relative to the size of the letter stimuli. The box was presented such that the probed letter would appear centered within it. The outline of the box was black and had a line thickness comparable to that of the letter stimuli (.10°). The trial sequence following the presentation of the test-display was identical to that in Experiment 2.



Figure 10. Illustration of cue type in Experiment 3. Left: non-masking cue. Right: masking cue.

Results and Discussion

On the basis of the same criteria as in Experiment 2, 12.3% of the trials were eliminated from further analysis. Average latency and duration of the saccades from the center of the circular array to the saccade target location on the remaining trials was 213 ms and 57 ms (range 35-79 ms), respectively.

Change detection performance (Figure 11) was analysed in a repeated-measures ANOVA with trial type and relative probe position as within-subject variables. The analysis revealed a main effect of trial type, $F(3, 6) = 23.43, p < .001, MSE = .0026$, and relative probe position, $F(4, 8) = 145.51, p < .0001, MSE = .0022$. In addition, the interaction between trial type and relative probe position was significant, $F(12, 24) = 3.44, p < .005, MSE = .0016$.

Similarly to Experiment 2, detection of changes in the saccade target item showed ceiling performance, regardless of trial type.

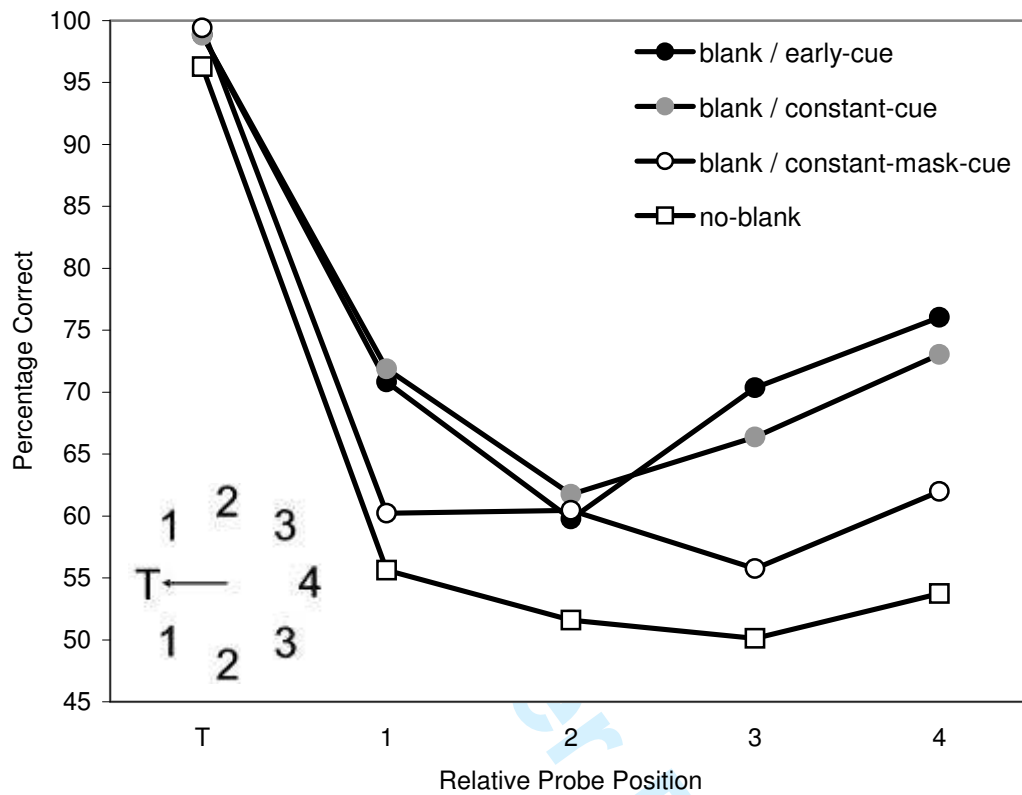


Figure 11. Percentage correct detection in Experiment 3 as a function of relative probe position (T = saccade target) and trial type.

Reanalysis of the data, excluding trials in which the saccade target was probed, revealed main effects of both trial type, $F(3, 6) = 20.65, p < .002, MSE = .0035$, and relative probe position, $F(3, 6) = 5.27, p < .05, MSE = .0029$. The interaction between the two factors disappeared, $F(9, 18) = 1.97, p = .11, MSE = .0018$. Change detection performance for non-saccade target items was 52.6% in the no-blank, 59.3% in the blank / constant-mask-cue, 67.6% in the blank / constant-cue, and 68.3% in the blank / early-cue condition. Planned comparisons between the no-blank condition and blank / early-cue condition, revealed a significant blanking effect, $F(1, 2) = 35.53, p < .03, MSE = .0046$. Performance in the blank /

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3 early-cue condition, which served as a control condition, was better than in the blank /
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5 constant-mask-cue condition, $F(1, 2) = 24.68, p < .04, MSE = .0030$, but did not differ from
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7 the blank / constant-cue condition ($F < 1$). The difference between performance in the blank /
8
9 constant-mask-cue condition and no-blank condition did not reach significance, $F(1, 2) =$
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11 $5.12, p = .15, MSE = .0011$.
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15 The results can be summarized as follows. First, similar to the Experiment 2, detection
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17 of changes to the saccade target item was almost perfect. The fact that the presentation of a
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19 masking cue during the 950 ms blanking interval did not affect performance for the saccade
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21 target item, shows that the transsaccadic representation of a saccade target object is held in a
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23 durable, non-maskable store, presumably VSTM. Second, a blanking effect for non-saccade
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25 target items was again observed in both conditions with a non-masking cue. Third, the
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27 blanking effect severely decreased when a square-like cue instead of a small red disk was
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29 presented at the location of the to-be-probed item during the entire blanking interval. This
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31 suggests that the representation that supports the blanking effect is susceptible to masking,
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33 which is consistent with the properties of a visual analog.
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39 Note that masking was spatiotopic. It has indeed been suggested that informational
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41 persistence is organized spatiotopically. This seems to stand in contrast to proposals that a
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43 spatiotopic representation is not necessary for explaining transsaccadic visual stability.
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45 Instead, stability could be based on a remapping of retinotopic representations (e.g., Melcher
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47 & Colby, 2008), maybe even implemented in the brain as the remapping of the receptive
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49 fields of neurons (Duhamel, Colby, & Goldberg., 1992; Colby & Goldberg, 1999; but see
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51 Cavanagh, Hunt, Afraz, & Rolfs, in press). However, we agree with Melcher that theories
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53 stressing remapping and theories with a spatiotopic focus “are not necessarily mutually
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55 exclusive and may, instead, capture different aspects of a process that aligns – across saccades
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57 or other body movements – the network of spatial maps in the brain that encoded objects and
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actions ” (Melcher, 2009, p. 1250). Moreover, we want to argue that, contrary to existing accounts on the basis of predictive remapping, transsaccadic representations are not restricted to objects that received attention presaccadically.

Experiment 4

The results obtained in the previous experiments suggest that the representation that supports the blanking effect decays fairly rapidly, requires selective attention to be used, and is susceptible to masking. So far these properties are all in line with the characteristics of a transsaccadic visual analog. In Experiment 4, we examined another property of the visual analog. In the within-fixation Experiment 1, it was shown that read-out from the visual analog and transfer to VSTM is a time-consuming process: Detection performance increased when more time was available for read-out from the visual analog and transfer to VSTM. If selective read-out from the visual analog is responsible for the blanking effect observed in the transsaccadic experiments, then read-out and transfer of information should show the same properties as in the fixation experiment. That is, read-out and transfer to VSTM should be relatively slow and interrupted whenever a new stimulus appears in the visual field.

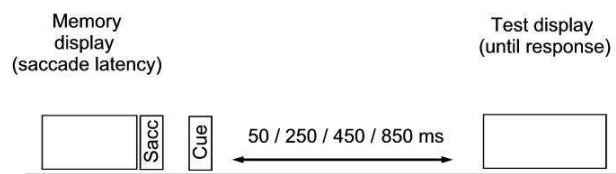


Figure 12. Schematic illustration of events and time course of a trial in Experiment 4 (Sacc = saccade).

To test whether this property can also be observed in a transsaccadic change detection paradigm, Experiment 4 included four conditions in which the time available for read-out and transfer was manipulated. As shown in Figure 12, in all four conditions, the test display was

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3 blanked for a certain period of time. A non-masking cue was always presented 50 ms into the
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5 blanking interval for a period of 50 ms. Following offset of the cue, the time available for
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7 read-out of the visual analog representation and transfer to VSTM was manipulated. The time
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9 between offset of the cue and the appearance of the test display was 50, 250, 450, or 850 ms.
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12 Method

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15 Participants. Two paid University of Leuven students, all reporting normal vision, and
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17 the first author participated in Experiment 4.
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20 Procedure. The trial sequence prior to the critical saccade to the saccade target letter
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22 was identical to Experiments 2 and 3. During this saccade, the screen was cleared and 50 ms
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24 after saccade landing, a non-masking cue was presented for a duration of 50 ms. The cue was
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26 again a red disk, identical to that used in Experiments 2 and 3, presented at one of the
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28 locations previously occupied by a letter. Following offset of the cue, the screen was still
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30 blanked for a variable period of time and then the test display appeared. The time between
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32 offset of the cue and the appearance of the test display, further referred to as post-cue
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34 blanking time, was either 50 ms, 250 ms, 450 ms, or 850 ms. Once the test display was
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36 presented, the procedure was identical to that in the previous experiments.
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41 Results and Discussion

42
43 11.9% of the trials were eliminated from further analysis. Average latency and
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45 duration of the saccades to the saccade target location on the remaining trials was 211 ms and
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47 56 ms (range 36-79 ms), respectively.
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51 Change detection performance (Figure 13) was analysed in a repeated-measures
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53 ANOVA with post-cue blanking time and relative probe position as within-subject variables,
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55 which revealed main effects of post-cue blanking time, $F(3, 6) = 29.07$, $p < .0006$, $MSE =$
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57 $.0009$, and relative probe position, $F(4, 8) = 466.80$, $p < .0001$, $MSE = .0006$. In addition, the
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59 interaction between post-cue blanking time and relative probe position was significant, $F(12,$
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24) = 2.36, $p < .04$, $MSE = .0014$. As expected, detection of changes in the saccade target item showed ceiling performance, regardless of post-cue blanking time.

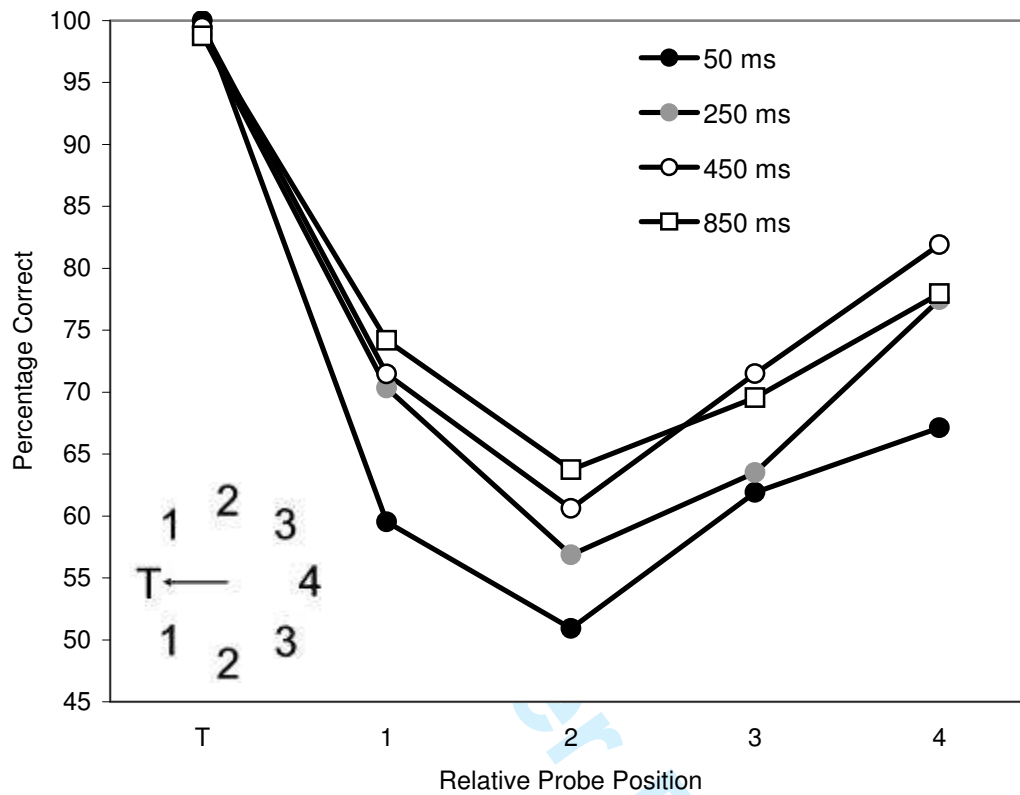


Figure 13. Percentage correct detection in Experiment 4 as a function of relative probe position (T = saccade target) and post-cue blanking time.

Reanalysis of the data, excluding trials in which the saccade target was probed, showed main effects of both post-cue blanking time, $F(3, 6) = 28.79$, $p < .0006$, $MSE = .0012$, and relative probe position, $F(3, 6) = 110.87$, $p < .0001$, $MSE = .0006$. In addition, the interaction between the two factors disappeared ($F < 1$). Change detection performance for non-saccade target items was worst when post-cue blanking time was limited to 50 ms (58.8% correct). Performance gradually increased with longer post-cue blanking times (65.5% correct with 250 ms blanking time) and asymptoted once post-cue blanking time reached 450 ms (69.9% and 70.4 % correct with 450 and 850 ms blanking time respectively). This suggests

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3 that, in order to obtain a blanking effect, a certain amount of time is needed between the
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5 presentation of a cue during the blanking interval and the onset of a new stimulus. This result
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7 is in agreement with what was found in the within-fixation Experiment 1. We interpreted this
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9 effect in terms of a relatively slow read-out and transfer process from the visual analog to
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11 VSTM, which is interrupted whenever a new stimulus appears in the visual field. The strong
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13 resemblance between the within-fixation results and the present results obtained within a
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15 transsaccadic blanking paradigm suggests that the representation supporting the transsaccadic
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17 blanking effect is the same visual analog representation.
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22 Experiment 5

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24 Experiment 5 aimed at exploring transsaccadic memory given a better approximation
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26 of object perception as achieved during real-world scene perception. While eye movements in
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28 scene exploration are generally initiated from a foveal object (i.e., the saccade source) to some
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30 object in peripheral vision (e.g., De Graef et al., 1990; Einhäuser, Spain, & Perona, 2008;
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32 Henderson & Hollingworth, 1998), this was not the case in Experiments 2-4. In these
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34 experiments, participants were required to saccade from an empty location to a designated
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36 saccade target object. This situation differs in terms of both attentional and oculomotor
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38 demands from one in which a to be identified source object is present in foveal vision prior to
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40 saccade initiation. In fact, the presence of a source object creates a foveal load that may
41
42 attenuate the quality, duration, and spatial extent of extrafoveal processing (Henderson &
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44 Ferreira, 1990; Ikeda & Takeuchi, 1975; Kennedy, 1998; Liversedge & Findlay, 2000). To
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46 explore possible effects of foveal load on transsaccadic memory, Experiment 5 included
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48 blanking and no-blanking conditions in which viewers either initiated a saccade from an
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50 empty location (cf. Experiments 2-4) or from a central source object to a designated target
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52 object.
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3 Experiment 5 contained two blanking conditions, in which a 50 ms cue was presented
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5 50 ms following saccade landing. The first was a condition without foveal load, identical to
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7 the blank / early-cue conditions of Experiments 2-4. The second blanking condition was
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9 identical to the first with the exception that an additional letter (further referred to as the
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11 source item) was presented in the centre of the presaccadic display (blank / early-cue-foveal-
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13 load). In this condition, participants were instructed to encode the source and then make an
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15 eye movement to the saccade target. In one ninth of the trials the source was cued during the
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17 blanking interval. In addition to the blanking conditions, two no-blanking conditions, one
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19 without foveal load (no-blank / no-foveal load) and one with foveal load (no-blank / foveal-
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21 load) were introduced. As in the previous experiments, the no-blanking conditions served as a
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23 baseline to assess the blanking effect.
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29 Change detection performance for the saccade target in the previous experiments (i.e.,
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31 without foveal load) was almost perfect under blanking (with and without cueing) and no-
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33 blanking conditions, suggesting that the target, which receives selective attentional processing
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35 prior to saccade execution, was stored in VSTM. Introducing a foveal source may decrease
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37 the extent to which the target is processed prior to saccade execution. This implies that in the
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39 condition without blanking, which is assumed to reflect change detection based on a VSTM
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41 representation, we may observe a decline in performance when a source is present (i.e., no
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43 ceiling performance for the target as observed in the no-blanking conditions of Experiments 2,
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45 3, and 4). If this is indeed observed, a blanking effect on the target object may reveal itself
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47 (e.g., De Graef & Verfaillie, 2002; Deubel et al., 2002).
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53 For the bystander objects, performance in the previous experiments (i.e., without
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55 foveal load) was almost at chance in the conditions without blanking, and improved strongly
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57 when a blank together with a cue was presented following saccade landing. In Experiment 5,
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59 we were specifically interested to see whether this blanking effect would still hold in the
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3 presence of a foveal source. Under the assumption that a preattentive visual analog supports
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5 improved performance for bystander objects under blanking conditions, we expected a similar
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7 effect.
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10 Method

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12 Participants. Two paid University of Leuven students and the first author participated
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14 in Experiment 5. All participants reported normal vision.
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18 Procedure. The procedure was identical to previous experiments with the following
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20 exceptions. Similar to previous experiments, the initial letter display contained a circular array
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22 of eight letters. In trials without foveal load, the central location was empty, whereas on trials
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24 with foveal load, an additional letter was presented at the centre of the circular array (i.e., the
25
26 source). This letter was chosen from the 8 remaining letters that did not appear in the circular
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28 array. In addition to the letter stimuli, the initial display contained a 2° radial line segment that
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30 indicated the letter to which a saccadic eye movement had to be made. On blanking trials, the
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32 postsaccadic display was blanked for 950 ms and a cue (50 ms duration presented 50 ms
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34 following saccade landing) was presented indicating which location would be probed in the
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36 test display. In the blanking condition with foveal load, the cue was presented centrally in one
37
38 ninth of the trials. The test display always contained a single item, presented at the cued
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40 location. For the foveal load condition, this meant that the source was probed in one ninth of
41
42 the trials. The no-blank / no-foveal-load and no-blank / foveal-load conditions were identical
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44 to their respective blanking conditions, with the exception that the test-display was present
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46 directly following saccade landing.
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54 Design. Each subject participated in three practice blocks and 16 experimental blocks
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56 of 136 trials. Each participant completed 1024 no-foveal load trials, which were a factorial
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58 combination of 2 conditions (no-blank / no-foveal-load and blank / no-foveal-load), 8 saccade
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60 target locations, 8 possible letter change positions, 2 change conditions (same or different),

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3 and 4 repetitions, and 1152 foveal load trials, which were a factorial combination of 2
4 conditions (no-blank / foveal-load and blank / foveal-load), 8 saccade target locations, 9
5 possible letter change positions (eight locations on the circular array plus the central location),
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10 2 change conditions (same or different), and 4 observations. In total each participant
11 completed 2176 experimental trials. The experiment was completed in 5 sessions (one
12 practice session and four experimental sessions), which each lasted approximately 1 hr 20
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15 min.
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19 20 Results and Discussion

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22 On the basis of the same criteria as in Experiment 2, 11.2% of the trials were
23 eliminated from further analysis. Saccadic latencies were on average 39 ms longer with foveal
24 load than without foveal load, with an overall mean of 226 ms. Average duration of the
25 saccades was 57 ms (range 37-78 ms).
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32 Figure 14 shows detection performance as a function of blanking, foveal load, and
33 relative probe position. Unlike the previous experiments, relative probe position now has 6
34 instead of 5 levels. This is due to the foveal load conditions in which the source could be
35 probed. Because the source cannot be probed in the no-foveal load conditions, relative probe
36 position in those conditions had only five levels. As shown in Figure 14, when the probed
37 item was either the source item (in the foveal load conditions) or the saccade target item,
38 change detection performance was near perfect regardless of trial type. Because ceiling
39 performance was observed for the source and the saccade target, and because relative probe
40 position in the no-foveal load conditions does not include data on the source, we focused the
41 analysis on non-target and non-source items, which will be referred to as bystander items (i.e.,
42 relative probe position 1 to 4).
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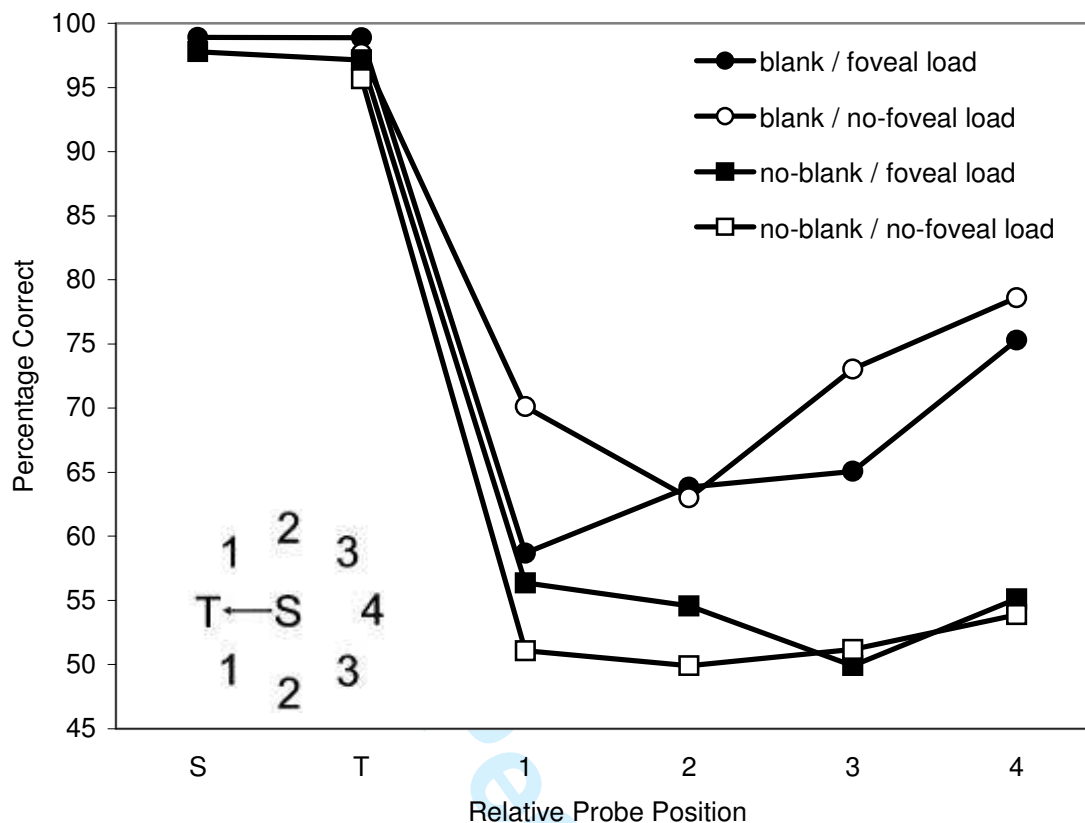


Figure 14. Percentage correct detection in Experiment 5 as a function of relative probe position (*S* = source, *T* = saccade target) and trial type.

Change detection performance, expressed as the percentage correct responses, was analysed in a repeated-measures ANOVA with blanking, foveal load, and relative probe position (1 to 4) as within-subject variables. The analysis revealed main effects of both blanking, $F(1, 2) = 262.50, p < .004, MSE = .0011$, and relative probe position, $F(3, 6) = 21.32, p < .002, MSE = .0007$. There was no significant main effect of foveal load, $F(1, 2) = 1.19, p = .39, MSE = .0020$. In addition, the interaction between blanking and foveal load was significant, $F(1, 2) = 192.74, p < .006, MSE = .0001$. No further interactions involving any of the factors were observed ($ps > .15$).

Following up on the interaction between blanking and foveal load, there was no effect of foveal load under no-blanking conditions, $F(1, 2) = 2.55, p = .25, MSE = .0014$. Mean

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3 proportions correct in the no-blank / no-foveal-load and no-blank / foveal-load conditions
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5 were respectively 51.2% and 53.8%. Under blanking conditions, foveal load caused a
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7 significant decrease in performance, $F(1, 2) = 27.33, p < .04, MSE = .0006$. Mean percentages
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9 correct in the blank / no-foveal-load and blank / foveal-load conditions were respectively
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11 69.9% and 64.4%. Together, these results show that foveal load only affected change
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13 detection performance for bystander items when the postsaccadic display was blanked. The
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15 effect of blanking was significant under both no-foveal load, $F(1, 2) = 714.12, p < .002, MSE$
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17 $= .0006$, and foveal load conditions, $F(1, 2) = 92.97, p < .02, MSE = .0009$.
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22 To summarize, the present results show that items presented at fixation during the
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24 presentation of the memory display (i.e., the source item) were perfectly encoded, retained,
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26 and integrated with new information following the saccade, regardless of whether the
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28 postsaccadic display was blanked or not. The same is true for saccade target items; change
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30 detection performance was near perfect in both blanking and no-blanking conditions.
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32 Furthermore, performance for the target was not affected by the presence of a presaccadic
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34 source item. This suggests that the source and the target, which receive selective attention
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36 prior to saccade execution, were durably stored, presumably in VSTM.
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41 For bystander items, a completely different pattern of results was observed. Under
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43 normal circumstances, that is, no-blanking conditions, change detection performance was at
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45 chance (52.5% on average), suggesting that bystander items may not have been encoded at
46
47 all. However, similarly to our previous transsaccadic experiments, change detection
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49 performance increased drastically when the postsaccadic display was blanked (reaching
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51 67.3% on average). This result clearly indicates that bystander items were encoded
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53 presaccadically, even when change detection failed completely in the no-blanking conditions.
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55 Blanking the postsaccadic display and directing focused attention to the to-be-probed item
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3 location enables the visual system to use information, presumably in the form of a visual
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5 analog, that is otherwise inaccessible for change detection purposes.
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8 More important with regard to the aim of the present experiment is the observation of
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10 a blanking effect when the presaccadic display contained a foveal source object. Change
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12 detection performance in the foveal load conditions showed a significant improvement when
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14 the postsaccadic display was blanked (53.8% vs. 64.4%). This is an important finding because
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16 it generalizes the blanking effect for bystanders to a situation that is a better approximation of
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18 normal object perception (i.e., a situation in which a saccade is initiated from a to-be-
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20 identified foveal source object instead of an empty location). However, foveal load did affect
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22 the magnitude of the blanking effect. That is, less information on bystander items seemed to
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24 be regained under blanking circumstances when the presaccadic display contained a foveal
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26 source item than when it did not. Performance in the blanking condition with foveal load was
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28 approximately 5 percent worse compared to the no-foveal load condition (i.e., 64.4% vs.
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30 69.9%). We return to this in the General Discussion.
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36 General Discussion

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38 The present study assessed what kind of information is retained and integrated across
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40 a saccade. Previous research suggests that transsaccadic integration is supported by a durable,
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42 relatively abstract, and capacity-limited memory store, presumably VSTM. However, recent
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44 studies seem to indicate that more detailed location and form information can be remembered
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46 across a saccade than could be expected based on the characteristics of VSTM. In particular,
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48 when a target to which an eye movement is made, is absent during the saccade and for a short
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50 period at the beginning of the postsaccadic fixation (i.e., blanking), the visual system seems to
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52 regain access to more detailed information compared to a situation without blanking (De
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54 Graef & Verfaillie, 2002; Deubel et al., 1996, 1998, 2002; Gysen et al., 2002). De Graef and
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56 Verfaillie (2002) suggested that the transsaccadic blanking effect might be supported by a
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3 representation similar to the visual analog as observed in within-fixation experiments (i.e., a
4 high-capacity, non-selective, maskable representation of the form and location of objects,
5 which decays approximately 300 ms following stimulus offset; Di Lollo & Dixon, 1988;
6 Irwin & Yeomans, 1986). The goal of the present study was to further assess whether
7 transsaccadic memory is restricted to a VSTM representation or, as suggested by De Graef
8 and Verfaillie (2002), whether it also contains a representation similar to the visual analog.
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The results of Experiment 1 confirm previous findings that, within fixations, both a durable, but capacity limited VSTM representation and a non-selective, maskable, relatively fast decaying visual analog representation play a role. Beyond this distinction, we have shown that selectively attending a cued location after stimulus offset enables read-out and transfer of information from the visual analog to VSTM, where it can be stored for subsequent comparison with items in the test display. However, if the cued item is not retrieved from the visual analog, because either the read-out and transfer process from the visual analog to VSTM is interrupted by the appearance of a new stimulus, or decay of the visual analog representation has reached the point where it cannot be read out properly, change detection will be determined by the presence or absence of a representation of that item in VSTM. In the latter case, the VSTM representation is created during presentation of the test display, whereas in the first, the VSTM representation is created after presentation of the cue, that is, following read-out of the visual analog.

Four transsaccadic change detection experiments were carried out to investigate whether memory across fixations is restricted to VSTM representations or whether it also includes a visual analog component. Experiment 2 served to answer three questions. First, is the blanking effect restricted to the saccade target object or can it also be observed for bystander objects? Second, is blanking in itself a sufficient condition to obtain an increase in change detection performance or is focused attention at the to be probed item location during

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3 the blanking interval necessary? Third, if focused attention is needed, does postponing the
4 redirection of attention to the to be probed item location reduce the blanking effect? If the
5 blanking effect is supported by a visual analog representation, we expected blanking effects
6 for both saccade target and bystander objects, but only if the to be probed item location is
7 given focused attention and this within a restricted timeframe following saccade initiation.
8 Experiment 2 confirmed these predictions. Change detection for the saccade target was almost
9 perfect under no blanking conditions, while detection of changes in bystander items was
10 extremely poor, presumably indicating that presaccadic attention allocation was restricted to
11 the target, limiting coding in VSTM largely to this object. Moreover, blanking in itself did not
12 improve change detection for bystanders, while blanking and at same time cueing the location
13 of the to be probed item did. In addition, the blanking effect was reduced if the cue, which is
14 assumed to redirect attention, was postponed, supporting the hypothesis of a relatively fast
15 decaying visual analog.
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34 In Experiment 3, we investigated whether the transsaccadic representation that
35 supports the blanking effect is susceptible to masking, which would be consistent with the
36 properties of a visual analog. Of main interest was a comparison between the magnitude of
37 the blanking effect in two blanking conditions with different cues presented throughout the
38 blanking interval (relative to a no-blanking control condition). The presentation of a masking
39 cue (a square box presented in such a way that a letter could fit within its contours) during the
40 blanking interval did not affect detection performance for the saccade target object, indicating
41 that this item was stored in a durable, non-maskable store, presumably VSTM. However, for
42 bystander items the blanking effect observed with the masking cue (the square box) was
43 severely reduced relative to the non-masking cue (a small red disk). In fact, the blanking
44 effect with the masking cue did not reach significance.
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3 The within-fixation Experiment 1 showed that it takes a certain amount of time to read
4 out and transfer information from the visual analog to VSTM. Moreover, this read-out and
5 transfer process was shown to be interrupted by the appearance of a new stimulus. In
6 Experiment 4, we tested whether these properties, associated with a visual analog, could also
7 be observed in a transsaccadic context. More specifically, the time between offset of the cue
8 and the appearance of the test display (i.e., post-cue blanking time) was manipulated and
9 ranged between 50 and 850 ms. Detection performance for the saccade target was almost
10 perfect and unaffected by post-cue blanking time. However, for bystander items a similar
11 pattern of results was obtained as in the within-fixation experiment: Performance improved
12 with increasing post-cue blanking time and then asymptoted, suggesting an analogous read-
13 out and transfer process from the visual analog to VSTM, which is interrupted by the
14 appearance of a new stimulus.

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32 Finally, Experiment 5 examined the blanking effect given a better approximation of
33 object perception as achieved during real-world scene perception. Instead of having viewers
34 saccade from an empty location to a designated target object (no foveal load), participants
35 initiated a saccade from a foveal source object on half of the trials (i.e., foveal load). Change
36 detection was almost perfect for the saccade source and the target object, indicating that
37 selectively attended objects prior to saccade execution, were durably stored, presumably in
38 VSTM. Furthermore, a blanking effect for bystanders was observed when the presaccadic
39 display contained a foveal source object. However, foveal load did affect the magnitude of the
40 blanking effect. Performance in the blanking condition with foveal load was slightly reduced
41 compared to the condition without foveal load.

42 The transsaccadic visual analog

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60 Experiments 2-5 provide evidence that transsaccadic memory includes a highly
reliable representation, which seems to be restricted to objects that receive selective

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3 attentional processing prior to saccade execution (i.e., normally the saccade target and source
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5 object; also see De Graef, Verfaillie, & Lamote, 2001; Currie, McConkie, Carlson-
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7 Radvansky, & Irwin, 2000; McConkie & Currie, 1996; Verfaillie & De Graef, 2000). This
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9 representation proved to be durable (i.e., showed no signs of decay), resistant to masking, and
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11 readily accessible for change detection purposes, suggesting that transsaccadic memory
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13 includes a VSTM representation of presaccadically attended objects. The present experiments
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15 however, indicate that transsaccadic memory is not restricted to VSTM representations.
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17 Instead, it also seems to include a more volatile representation, which, under normal
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19 circumstances, is inaccessible for change detection purposes. Consistent with previous studies
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21 (De Graef & Verfaillie, 2002; Deubel et al., 1996, 1998, 2002; Gysen et al., 2002), the visual
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23 system only appears to regain access to it if the postsaccadic image is blanked for a certain
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25 amount of time.
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32 On the one hand, comparison of the characteristics of the visual analog as observed in
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34 the within-fixation Experiments 1 with those of the representation supporting the
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36 transsaccadic blanking effect showed remarkable similarities - the necessity of blanking and
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38 cueing (and associated attentional orienting), the relatively fast decay, and the time-
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40 consuming read-out, which can be interrupted by a mask -, suggesting that the blanking effect
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42 reflects the use of a visual analog similar to that observed in within-fixation conditions.
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46 On the other hand, some of the results seem to question the idea that the transsaccadic
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48 visual analog is completely identical to its within fixation version. First, despite the fact that
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50 change detection performance improved considerably under blanking conditions in the
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52 transsaccadic experiments, performance was far from perfect (e.g., approximately 72%
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54 correct in the blank / early-cue condition of Experiment 2). Yet, in the within-fixation
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56 Experiment 1, detection performance in the conditions that most closely match their
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58 transsaccadic counterparts was almost perfect (e.g., approximately 90% in the condition with
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3 a fixed ISI of 1000 ms and a cue delay of 100 ms). This result may suggest a fundamental
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5 difference between the transsaccadic visual analog and within-fixation visual analog in terms
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7 of capacity.
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10 A second finding that points in a similar direction was observed in Experiment 5. In
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12 this experiment, the blanking effect for bystanders was somewhat reduced when the
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14 presaccadic display contained a foveal source object. Although speculative, this reduced
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16 blanking effect may be understood in terms of a possible capacity limit in the transsaccadic
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18 visual analog. Under the assumption that the transsaccadic visual analog can only maintain a
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20 restricted number of items across a saccade, the foveally presented source item may have been
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22 maintained at the expense of other peripheral items in the array. More specifically, the
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24 number of unattended bystander items that can be maintained in the transsaccadic visual
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26 analog will then be reduced by one item. This hypothesis assumes a transsaccadic visual
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28 analog that faithfully represents a restricted amount of items. Furthermore, within this view,
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30 encoding of an object in the transsaccadic visual analog is assumed to be a necessary
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32 condition for subsequent attentional processing of an object prior to saccade execution. Thus,
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34 objects that receive selective attentional processing prior to saccade execution are then coded
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36 in both the transsaccadic visual analog and VSTM.
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43 This characterization of the transsaccadic visual analog may be intimately linked to
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45 the visual indexing or FINST (short for “fingers of instantiation”) theory as proposed by
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47 Pylyshyn (1989, 2001; Trick & Pylyshyn, 1994). This theory assumes an early preattentive
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49 stage in vision in which the location of properties of a small number of salient items are
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51 selected and indexed prior to any serial processes being applied to the visual array (e.g., prior
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53 to the allocation of limited attentional resources to an indexed item). In terms of transsaccadic
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55 integration, it has been argued that this preattentive, limited-capacity indexing mechanism
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57 may serve to establish spatiotemporal continuity of a restricted set of objects across a saccade
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3 (Hayhoe, Karn, Magnuson, & Mruzczek, 2001; Pylyshyn, 2001). As such, encoding of items
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5 in the transsaccadic visual analog may be based on and restricted to items that are spatially
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7 indexed prior to saccade initiation. Research on the allocation of visual indexes has also
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9 shown that indexes need not be assigned to contiguous, or nearby items in the visual array.
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11 Instead, indexes can get assigned to several disparate items scattered throughout the visual
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13 field (Bichot, Cave, & Pashler, 1999; Intriligator & Cavanagh, 1992; Sears & Pylyshyn, 2000;
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15 but see Dubois, Hamker, & Van Rullen, 2009).
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20 The notion of a limited-capacity transsaccadic visual analog may explain the absence
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22 of a blanking effect for bystander objects in the study by De Graef and Verfaillie (2002). In
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24 this study, the effect of blanking on the discrimination of intrasaccadic in-depth orientation
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26 changes of saccade target and bystander objects was examined. Even though transsaccadic
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28 memory for the saccade target showed a clear benefit from blanking, memory for the
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30 bystander did not. However, because stimuli consisted of complex scenes that contained a
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32 multitude of objects and viewers did not know in advance (i.e., prior to saccade initiation)
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34 which bystander would be probed in the postsaccadic display. If only a limited set of
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36 bystanders can be held in the transsaccadic visual analog, the likelihood that the to-be-probed
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38 bystanders would have been included is small in the presence of multiple objects. The saccade
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40 target, in contrast, would always be spatially indexed prior to saccade initiation, explaining
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42 the blanking effect for the saccade target.
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48 The distribution of the attentional field prior to the saccade

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51 The observation that performance for other stimuli than the saccade target mostly was
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53 not at chance level suggests that, in addition to the target stimulus, a nontarget stimulus could
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55 be attended (and transferred to VSTM) on a proportion of the trials. Moreover, performance
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57 was not equal for all nontarget locations. Instead, change detection was best when the
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59 stimulus diametrically opposite to the saccade target was probed and worst when the probed
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3 stimulus was at an intermediate distance from the saccade target. Similar effects have been
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5 documented before, but we can only speculate on the possible underlying mechanism.
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8 Studies in which subjects had to decide whether two precued stimuli on a circular
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10 array of letters were identical or different (e.g., Bahcall & Kowler, 1999; Skelton & Eriksen,
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12 1976) have shown that accuracy was highest for diametrically opposite pairs of cued targets
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14 (except for adjacent letters in Skelton & Eriksen's study). One possible explanation for this
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16 effect is that two letters in opposite locations on a circle stimulate opposite hemispheres.
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18 There is indeed evidence for superior visual processing when stimuli are presented in separate
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20 hemifields (Sereno & Kosslyn, 1991; also see Alvarez & Cavanagh, 2005; Delvenne, 2005).
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22 In the present study, letters that occupied positions that were 180° apart indeed always fell in
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24 opposite hemifields prior to saccade execution (the target was never presented in the exact top
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26 or bottom position of the circular array). However, Tse, Sheinberg, and Logothetis (2003)
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28 documented similar effects for stimuli arranged along the vertical axis and therefore not
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30 falling into separate hemifields (also see Müller & Kleinschmidt, 2004; Müller, Mollenhauer,
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32 Rösler, & Kleinschmidt, 2005).
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38 Of the experiments reported by Cutzu and Tsotsos (2003), the paradigm in their
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40 Experiment 4 comes closest to our paradigm. Subjects were presented with a circular array
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42 (with a radius of 4 degrees, as in our experiments) of 12 letters. The array contained rotated
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44 versions of all Ts or all Ls (target absent) or one L among Ts or one T among Ls (target
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46 present) and subjects had to detect an odd L among Ts (or vice versa). Prior to this test image
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48 (presented for 100 ms.), one letter location was precued for 180 ms. The findings were exactly
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50 the same as in our experiments. When the odd letter was at the cued location, detection
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52 accuracy was high. Away from the cue, accuracy initially decreased but then increased again,
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54 peaking when the target was diametrically opposite to the cued location. Cutzu and Tsotsos
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56 interpret their findings as evidence for the existence of an inhibitory zone, of annular shape
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3 and limited extent, surrounding an attended location, giving rise to a Mexican-hat shaped
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5 distribution of the attentional field. However, such an explanation would entail that the extent
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7 of the inhibitory annulus can be quite large (because both in Cutzu & Tsotsos' Experiment 4
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9 and in our experiments, accuracy was lowest for letters that were in an intermediate location
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11 between the cued letter and the letter at the opposite side of the ring of letters), while most
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13 studies supporting perceptual suppression around the attentional focus suggest smaller regions
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15 of suppression (see Müller et al., 2005, for an overview; also see Müller & Kleinschmidt,
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17 2004).

22 Tse et al. (2003; also see Tse, 2004) used a change-detection paradigm to map the
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24 distribution of spatial attention across the visual field in response to a task-irrelevant
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26 peripheral cue. Subjects were presented with a 25 degrees circular window with 149 possible
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28 locations, half of which were filled with equiluminant green or red squares. A cue was then
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30 briefly flashed in one of four possible locations, followed by a 47 ms. blank screen and a test
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32 display showing the original squares in addition to one new square in a previously unoccupied
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34 position. Subjects had to report the colour of the new square. The rationale behind this study
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36 was that the blank masks the local transient accompanying the appearance of the new element,
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38 thereby interfering with the detection of the change, and that only attention to a location both
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40 in the pre- and the postblank images can overcome this change blindness. The map of
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42 attentional distribution showed a "hot spot" of attention elongated along the fixation-cue axis
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44 with attention pooling not only at the cued location, but also at the location opposite the cued
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46 location. In this study (as well as in the studies reviewed above), subjects had to maintain
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48 fixation during a trial (or at least prior to the appearance of the test display). Tse et al. (2003)
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50 explicitly raise the question "whether opposite pooling [of attention] occurs even when
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52 observers are permitted to saccade to the cue" (p. 98). The present study for the first time
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54 shows that this is indeed the case. Apparently, an attention shift as a preparatory process for a
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3 saccadic eye movement stretches the attentional beam along an axis defined by the attentional
4 focus prior to the shift of attention (mostly the foveal stimulus) and the target of the relocation
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6 of attention (e.g., a peripheral cue). Moreover, the data of Tse et al.'s study in which subjects
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8 had to maintain fixation, in combination with our data in which subjects were required to
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10 make a saccade, suggest that this elongation extends to locations opposite the target of the
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12 attentional (and eventually saccadic eye) shift.
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16 17 The possible functional role of the transsaccadic visual analog

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20 Our results support the hypothesis that transsaccadic memory holds a preattentive
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22 visual analog representation that may be capacity-limited. This transsaccadic representation
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24 only revealed itself under specific blanking circumstances. Because postsaccadic blanking
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26 never occurs in natural vision, the question arises what the functional role of a transsaccadic
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28 visual analog could be in a normal viewing situation (i.e., without blanking).
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32 Before speculating on this issue, it is important to note that a preattentive mechanism
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34 is never observed directly. What is observed in the present blanking studies are the
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36 postattentive consequences of a preattentive representational mechanism. Specifically, when
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38 the postsaccadic display was blanked and a bystander cued, read-out and transfer from the
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40 transsaccadic visual analog to VSTM, comparison between pre- and postsaccadic information,
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42 and a subsequent decision and response selection process are all likely to involve serial
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44 attentional components. Thus, exposing the presence of a transsaccadic visual analog always
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46 requires more than that preattentive representation itself, and these additional processes may
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48 be very specific to the blanking manipulation and the task of explicitly detecting
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50 intrasaccadic changes. In sum, this implies that the postattentive consequences observed by
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52 the blanking manipulation may only indirectly indicate the true functions of the preattentive
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54 representational system during normal transsaccadic object perception.
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3 But why, then, could a transsaccadic visual analog be useful in everyday vision? One
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5 of the principle functions of the visual system is to identify objects in the environment.
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7 Accordingly, during normal scene perception, transsaccadic memory may help object
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9 identification. While a single foveal view of an object may in principle be sufficient to
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11 identify an object, the preferred modus operandi in the exploration of the environment may be
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13 to increase speed and reliability of object identification by transsaccadic integration of foveal
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15 and extrafoveal evidence across a saccade. Several studies investigating transsaccadic object
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17 perception have shown that transsaccadic memory representations indeed speed up
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19 identification of elements in the postsaccadic image (e.g., Demeyer et al., 2009; Germeys, De
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21 Graef, & Verfaillie, 2002; Henderson, 1994; Henderson & Anes, 1994; Pollatsek et al., 1984,
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23 1990; Verfaillie, De Graef, Germeys, Gysen, & Van Eccelpoel, 2001). The hypothesis that we
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25 want to put forward is that a specific component of transsaccadic memory, namely the visual
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27 analog, plays an important role in this process of object identification across saccades. The
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29 visual analog can be regarded as reverberatory activity, allowing stimulus representations to
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31 remain active in the visual system after the corresponding objects have disappeared from the
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33 retina, thereby creating the possibility to integrate presaccadic and postsaccadic information
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35 in order to facilitate object identification. In other words, even though information stored in
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37 the visual analog normally remains inaccessible for conscious processes (so that it cannot be
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39 revealed except by creating artificial conditions, i.e., a specific combination of presaccadic
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41 cueing and postsaccadic blanking, to allow the visual system to store the information in a
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43 more durable VSTM), it expedites transsaccadic object identification at a preattentive level.
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53 This can be understood in the framework of the model of transsaccadic object
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55 identification, put forward by Germeys et al. (2002). While most accounts of transsaccadic
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57 preview benefits (i.e., facilitation by a peripheral preview on subsequent foveal object
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59 identification) have stressed the need for presaccadic allocation of attention to a peripheral
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3 object in order to obtain a preview benefit (e.g., Henderson, 1994; Henderson & Anes, 1994;
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5 Irwin, 1996), Germeys et al. (2002) observed preview benefits for both presaccadically
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7 attended (i.e., the saccade target) and non-attended objects (i.e., bystanders). Further results
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9 also showed that the representation supporting preview benefits for non-attended objects was
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11 strictly location bound. On the basis of these results, Germeys et al. (2002) proposed a model
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13 of transsaccadic object identification that includes a preattentive transsaccadic memory
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15 representation (in addition to an attentive representation). The model proposes that prior to
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17 saccade initiation, the visual system sets up a limited number of so-called 'preattentive object
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19 files'. These preattentive object files are created in parallel on the basis of preattentive
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21 grouping processes and hold a loose collection of unbound features that seem to belong
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23 together. Similar to FINST theory, each object file is location indexed, thus providing the
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25 visual system with a limited set of potential targets for subsequent attention and gaze shifts.
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27 Once this preattentive stage is completed, one preattentive object file is attentionally selected
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29 for further processing (i.e., feature binding), and if required, a saccade to the attended object
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31 is executed. In summary, this model assumes that transsaccadic preview benefits for
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33 unattended objects are produced by a limited set of location-indexed preattentive object files
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35 that are maintained across a saccade. Because of the similarity between this preattentive
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37 representation and the transsaccadic visual analog put forward on the basis of the present
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39 blanking experiments, it is tempting that they are in fact the same. Accordingly, the capacity
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41 limited transsaccadic visual analog may serve to aid transsaccadic object identification by
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43 providing memory for a limited number of preattentive object files, that, if selected for further
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45 attentional processes, may expedite object identification.
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