SECTION II

Change blindness and transsaccadic integration

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CHAPTER 7

Converging evidence for the detection of change without awareness

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Abstract: In this chapter, we explore the possibility that changes can be registered by the visual system and can influence behavior even in the absence of conscious awareness. We begin by describing the basic phenomenon of *change blindness*, introduce a framework for discussing some of the key issues relating to change detection as a whole, and then examine the main lines of evidence that point to the existence of *implicit change detection*.

Change detection

Change detection has very quickly become one of the most powerful and flexible experimental tools available to the vision researcher. While the long-term significance of this paradigm will almost certainly rest with the emphasis it places on the temporal aspects of vision — change is, after all, something that has to take place over time — its immediate appeal and success lies mainly with the striking phenomenology associated with one specific task, the flicker paradigm (Rensink et al., 1997).

In the flicker paradigm, which is illustrated in Fig. 1, two views of a complex scene are separated by a blank masking field and are alternated in the sequence: scene 1, blank, scene 2, blank, scene 1, blank, scene 2, and so on. The two scenes are identical, except for the presence of one changing item or scene location. Once the changing item has been detected it is clearly visible and often appears very 'obvious'. What is so compelling about this phenomenon is the extreme difficulty most observers usually have in locating the change, often taking many seconds of intense search, and sometimes failing to locate the change at all! (Rensink et al., 1997; Simons and Levin, 1997; Rensink, 2002a).

A crucial factor in making the change hard to detect appears to be the masking field. In addition to the blank field described above, other types of distracting events can be used, including blinks (e.g., O'Regan et al., 2000), saccades (e.g., Bridgeman et al., 1975; Grimes, 1996), movie cuts (Levin and Simons, 1997) and multiple small masking elements called 'mud splashes' (O'Regan et al., 1999). Subsequent work has also shown that the detection of change can also be difficult during virtual reality simulations (e.g., Wallis and Bülthoff, 2000), dynamic animation sequences (e.g., Scholl and Pylyshyn, 1999), side-by-side comparisons of images (the old 'spot the difference' game, Shore and Klein, 2000) and even real-world, face to face, interactions (Simons and Levin, 1998).

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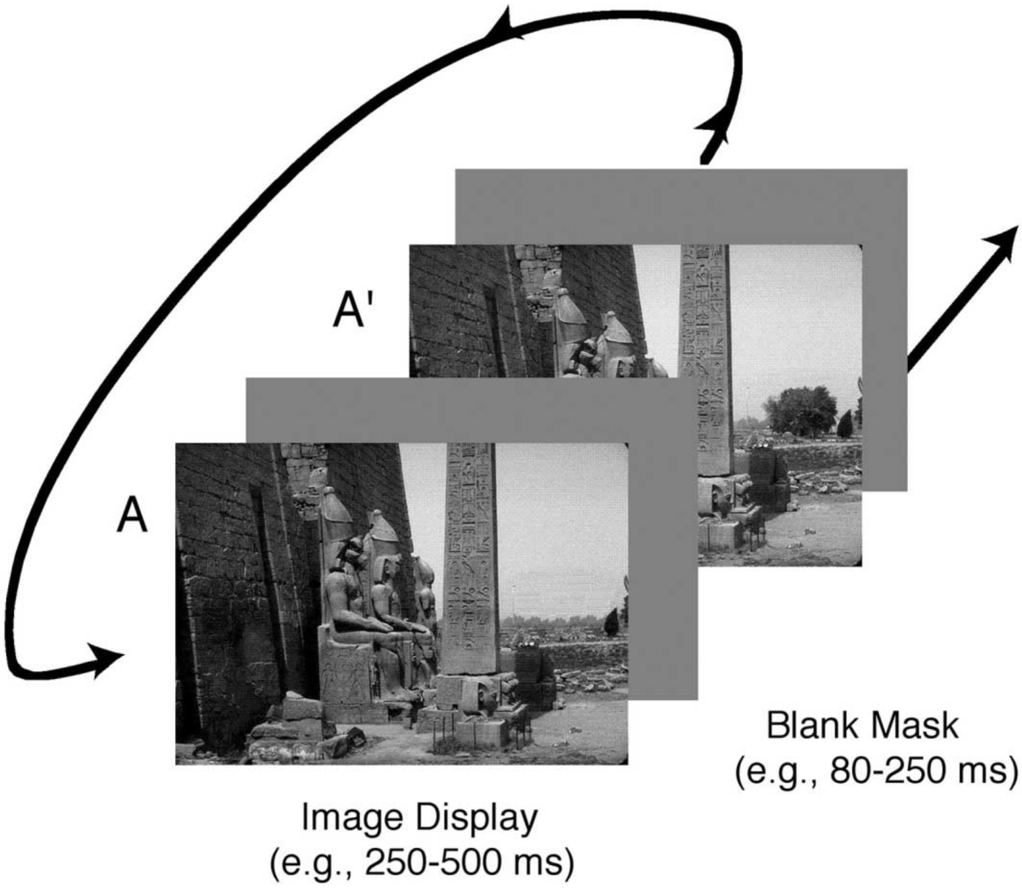


Fig. 1. An example of a flicker paradigm display (Rensink et al., 1997). Two views of a complex scene are separated by a blank masking field and are alternated in the sequence scene 1, mask, scene 2, mask, scene 1, mask, scene 2, and so on. These two scenes differ from one another only with respect to a single changing item or scene location. In this example, taken from the Cambridge Basic Research database, a large tree suddenly appears on the right of the screen in the second image.

Change blindness

In all of the above studies, the observer is asked to report the occurrence of a change. *Change blindness*, then, is operationally defined as a failure to become *explicitly aware* that a change is or was taking place. The main theme of this chapter is that such explicit reports of awareness underestimate the true impact of change. For now, however, we can ask 'why might an observer fail to report a change?'

Fig. 2 provides the framework within which we will explore this question, and other issues relating to change detection, during the current chapter. In later sections we provide a more detailed discussion, but here we note a few keys points:

- the separation of the visual registration of change, from the behavioral consequences of change;
- the creation of parallel attentional and non-attentional processing streams;
- the suggestion that awareness is only one of many behavioral consequences that might follow the registration of change.

A clear assumption in Fig. 2 is that both implicit and explicit detection of change are logically possible via either processing stream. As discussed in more detail below, this reflects a belief that spatiotemporally coherent representations – prerequisites for any form of change detection – can be constructed and maintained both with and without the involvement of attention during the registration

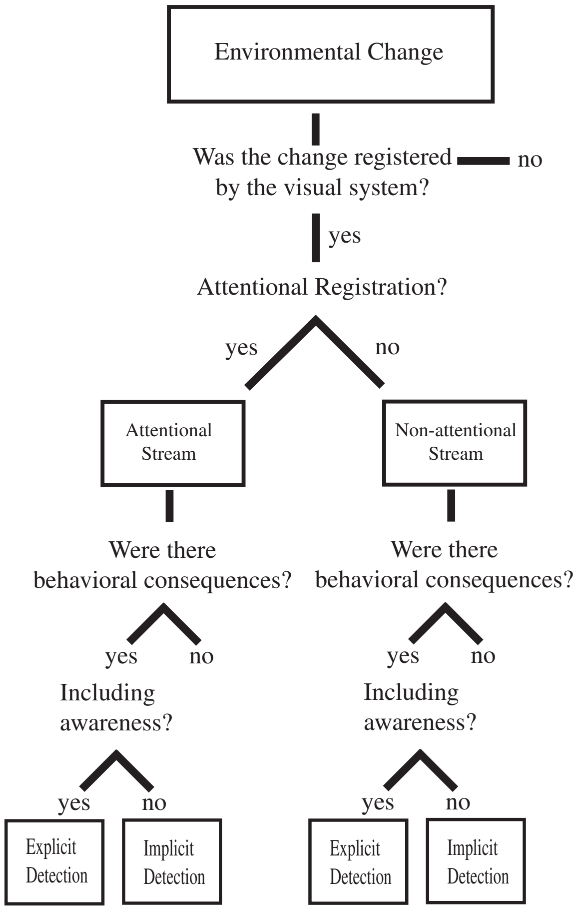


Fig. 2. A framework for exploring change detection. This simplified view of the stages involved in the explicit and implicit detection of change reflects the organization of the sections in the current chapter. Key points include: the separation of the visual registration of change, from the behavioral consequences of change; the creation of parallel attentional and non-attentional processing streams; the separation of the role attention may play in the formation of spatiotemporally coherent representations from its role in the modulation of awareness; the suggestion that awareness is only one of many behavioral consequences that might follow the registration of change. See text for more details.

of change. Furthermore, awareness is not seen as an unavoidable consequence of this registration process in either stream. That is, in the current framework, awareness is assumed to be an attribute which can be 'set' for any representation independent of the method of registration.

Note, that we are not suggesting that the probability of explicit or implicit detection would be equal across these two streams. For example, explicit detection may be much more likely for changes registered in the attentional stream because attention also plays an important part in modulating access to awareness. However, one of the main motivations for proposing this framework is the belief that these two processes — the *formation* of spatiotemporally coherent representations (i.e., registration) and the *modulation* of awareness — may in some sense be separable. We return to this issue later in the chapter.

In any event, the crucial qualitative difference between representations in this framework concerns their manner of registration — with or without attention — not the presence or absence of awareness.

Registration of a change

For an observer to be able to respond to a change in the environment, the visual system must register that change in some way. That is, the visual system must undergo an internal transformation reflecting the change in the environment. The result of such a transformational process is usually conceptualized as some form of *spatiotemporally coherent* mental representation. This concept captures the notion that the individual features or dimensions of a display must be bound together spatially, but also, for the registration of change, they must be connected or linked across time.

The visual system may fail to register a change for a number of reasons. The most obvious one would be a lack of encoding of the pre-change scene. This includes the trivial case in which sensory receptors are not available (e.g., closed eyes, adapted or fatigued receptors, etc.), to theoretically more interesting cases in which failure to encode the pre-change scene may stem from a lack of foveation or attention (e.g., Hollingworth and Henderson, 2002). Even if the pre-change scene is encoded, registration could fail if the blank mask or the changed image were to simply substitute the original image, erasing it from a visual buffer, and with no links being maintained across time. These are cases in which the change leaves no trace in the nervous system, so that the observer is truly blind to the change.

Of more interest in the current context are those changes that are registered by the visual system. As can be seen in Fig. 2, we draw an early and important distinction between those changes that may be registered via attentional mechanisms and those registered via non-attentional mechanisms. This distinction reflects a general belief that vision involves multiple processing systems that work together to support our successful interactions with the world. While it seems likely that many forms of processing occur without the direct involvement of attention, there is less agreement as to whether spatiotemporally coherent representations, needed for the registration of change, can exist in the absence of attention.

The dichotomy proposed here is clearly not intended to capture the full complexity of visual processing and visual attention. For example, within the attentional stream we have not distinguished between processing that might involve focused attention from that which involves distributed attention. Likewise, in the non-attentional stream, many candidate systems — each with their own specific form of representation — might operate in parallel, processing aspects of the scene such as its layout, its gist, or the actions it affords.

Attention

Focused attention is considered a key mechanism in establishing representations that are coherent across both space and time (Kahneman et al., 1992; Enns and Di Lollo, 1997; Rensink, 2000a, 2002a). Attention not only binds the individual features of objects or scenes together, but also ensures that identity is maintained across time. Indeed, it has been argued that without attention coherent representations cannot exist. That is, a number of researchers have suggested a general lack of object structure in the absence of attention (e.g., Treisman and Gelade, 1980). Furthermore, because of this, it has been suggested that our subjective impression of a detailed, stable representation of the physical world is little more than a 'Grand Illusion' (O'Regan, 1992). According to this view, we fail to notice that most of our visual world lacks detail and coherence because as soon as we 'look' at a new region of space, we bring that region into the focus of attention (Rensink, 2000b). Studies of change blindness have provided support for such claims (see Noë et al., 2000 for a further discussion).

There is little doubt that attention is crucially involved in explicit detection of change and theories on change blindness have relied heavily upon it. For example, the 'coherence theory' proposed by Rensink (2000a, 2002a) gives a central role to attention in its account of many empirical observations from the visual search and change blindness literature. The central role of attention in the explicit detection of change is also supported by a wealth of empirical evidence. For example, detection is greatly enhanced when attention is directed to the location of change, either by motion transients, object saliency (Rensink et al., 1997; Shore and Klein, 2000), semantic cues (Rensink et al., 1997), or exogenous cues (Scholl, 2000).

However, one concern with using the above findings to draw general conclusions about the nature of change registration stems from their almost complete reliance on explicit reports of awareness. Such a reliance is problematic for at least two reasons. (1) Awareness — or more precisely explicit report based on awareness — is only one of a whole range of behavioral consequences that could be used to measure the existence and impact of spatiotemporally coherent representations. As we will discuss below, there is increasing reason to believe that at least some of these alternative measures are more sensitive and/or more reliable indicators of change registration than subjective reports. (2) Drawing conclusions about the nature of representations based solely on subjective reports assumes a one-to-one relation between awareness and attention. In the next section, we suggest that this might not be the case.

Awareness

Given the central role that attention occupies in current theories of change blindness, it is important to highlight two possible contributions of attention to change detection. First, as we just noted, attention is important in establishing and sustaining the representation of change. Second, attention influences the conscious detection of change (i.e., helps the represented change reach visual awareness). Attention almost certainly plays a major role in determining the contents of conscious awareness. Indeed, attention and awareness are so closely linked that they are sometimes used interchangeably. They are not, however, synonymous. Attention has a functional role, modulating information processing. Awareness is perhaps best thought of as an attribute of the represented stimulus (Fernandez-Duque and Johnson, 1999). Attention may help to set this attribute — and indeed attention may prove to be a necessary ingredient — but other factors may also play a role.

These two roles of attention — establishing representations and modulating awareness — frequently coincide, as is the case in the explicit report of change. For this reason, they are often confounded. But does one necessarily entail the other? It remains a possibility that representations built or 'bound' by attention will fail to become consciously detected. Similarly, a representation of change may be constructed without attention, only to be affected by attention at a later time.

Recent studies suggest some support for these ideas, as changes to attended objects are sometimes missed. For example, the majority of observers fail to notice when the only actor in a short movie clip is replaced during a camera cut (Levin and Simons, 1997) or when the only partner in a conversation is replaced during a brief interruption (Simons and Levin, 1998; Levin et al., 2002). Similarly, changes made to items that are being monitored in an attentive tracking task (Pylyshyn and Storm, 1988) often go completely unnoticed (Scholl and Pylyshyn, 1999), as do changes to items that are being directly fixated (O'Regan et al., 2000).

These examples lend credibility to the claim that attending to an object, and binding its features across time into a coherent representation, do not always lead to the conscious detection of change. An additional comparison may be needed for the change to reach awareness (e.g., Scott-Brown et al., 2000; Simons, 2000; Hollingworth, 2002). Alternatively, attention may be a graded phenomenon, with awareness of change and representation of change having different thresholds. Another possibility is that attending to an object does not automatically give rise to coherent representations of *all* feature dimensions. Rather, the allocation of attention — and the resulting coherent representations — may be restricted to those feature dimensions that are engaged by the current task or observer strategy. Thus, changes may fail to be consciously detected unless attention has been allocated to the particular dimension or feature that is being updated.

Empirical evidence has also been gathered which relates to the second claim, that changes initially registered without attention can subsequently be affected when attention is allocated to them. If the attentional modulation of awareness is in any way independent from the attentional registration of change, it may be possible to become aware of an unattended change by attending to it *after* it has occurred. To explore this possibility studies have used a cue to direct attention to the location of change after the change has been completed. This post-cueing method suggests that some changes can be reported when a representation of the change — or possibly of the pre-change target — are retrieved from memory by the subsequent allocation of attention (Hollingworth, 2002, but see Becker et al., 2000).

Behavioral consequences

The behavioral consequence that has typically been explored in studies of change detection is the *explicit* report of a change that has reached awareness. In the remainder of this chapter, we explore the possibility that other behavioral consequences can also provide useful markers of change. When these additional consequences occur in the absence of awareness, then *implicit* detection of change has occurred.

Considering awareness as simply one possible behavioral consequence, rather than as the *only* indicator of spatiotemporally coherent representations, is important for several reasons. First, it motivates the search for additional ways to measure the impact of change. For example, various other aspects of behavior might be affected by a registered change, such as the speed and accuracy of direct responses (e.g., the speed with which the presence/absence judgements are made), the speed and accuracy of indirect responses (how the presence of a change might influence performance on a secondary task), or the patterns of eye and hand movements. Second, weakening the theoretical link between awareness and the representation of change allows for the possibility that such implicit effects arise either with or without the involvement of attention during the registration of change (see Fig. 2).

However, it also becomes clear that additional, independent methods for establishing the involvement of attention during change registration become necessary. That is, if we reject the notion that spatiotemporally coherence per se is a hallmark of attention, and we advocate a weakening of the attention–awareness link, then how can we establish when attention is involved in representing change? Clearly, when exploring the role of attention in this context, additional indirect measures, such as behavioral signatures (e.g., spatial cueing effects), neural markers, and/or visuo-motor patterns (e.g., saccade targeting) should also be taken into account.

Implicit processing

The notion that changes may be detected without the involvement of conscious awareness receives credibility from similar findings in other domains. There is a rich literature showing that information can be represented in the brain and have an impact on behavior, without such processing leading to awareness. Classic studies of amnesic patients (Milner et al., 1968) first raised the possibility that memory representations could affect performance in the absence of explicit recall or recognition of stored information (see also, Jacoby et al., 1993; Schacter, 1995 for studies with normal observers). The sequence learning literature (see Clegg et al., 1998, for a review) also demonstrated that complex patterns of behavior could be adopted without explicit awareness (Curran and Keele, 1995; Destrebecqz and Cleeremans, 2001). Similar claims have come from studies of perception/action dissociations (Goodale, 1996).

There is also a growing body of work demonstrating that perceptual processing can often proceed outside of awareness (e.g., Marcel, 1983; Graves and Jones, 1992; Kolb and Braun, 1995; Luck et al., 1996; McCormick, 1997; Moore and Egeth, 1997; Bar and Biederman, 1998; Chen, 1998; Mack and Rock, 1998). In a classic study by Marcel (1983), two probes were presented following a masked word. Observers reported whether or not a word preceded the mask (detection task), which probe most closely resembled the masked word (graphic task), and which probe was semantically closest to the word (semantic task). Even when observers could not consciously detect the presence of the word, they could 'guess' at better than chance levels in the graphic and semantic tasks. These findings indicate that form and meaning can be processed without awareness. Furthermore, the presence of an unaware prime congruent with a target facilitates response during lexical decision (Marcel, 1983) and naming tasks (Carr et al., 1982), and these effects are sometimes as large as when subjects are fully aware of the prime (Fowler et al., 1981; Carr et al., 1982).

More recently, Dehaene et al. (2001) have used ERP and fMRI techniques to examine the neural processing that accompanies such implicit effects. They found that masked stimuli engaged a fairly high-level processing stream, including extrastriate cortex, left fusiform gyrus and the precentral sulcus, suggesting fairly sophisticated implicit processing. In a second experiment a repetition priming paradigm was used to show that these identified regions could be selectively adapted, indicating that the meaning of the word had be extracted without awareness. ?#1

Implicit perception is not restricted to word processing. Similar findings have also be reported with number processing (Dehaene et al., 1998) and object recognition. For instance, Bar and Biederman (1998) used a backwards masking procedure to present pictures of objects outside of observers' explicit awareness. Lack of awareness was established using an objective criterion of chance performance in a four-alternative forced-choice recognition task. In the test phase, 15 minutes later, priming was found when the exact same objects were presented (identity prime) and this effect was even larger when the objects were presented at the same location (location prime). Objects with the same name but different shape were not primed. This absence of implicit semantic priming in the presence of implicit identity priming may hint at differences in the type of content that can be implicitly represented. Alternatively, the absence of semantic priming in this study may be due to the fact that the semantic effects of unaware primes are usually short lived (Greenwald et al., 1996).

Finally, Chun and Nakayama (2000) have suggested that successful visual interactions with the world could not proceed unless implicit visual memory mechanisms were helping us to select and retain information across space and time. They discuss two such mechanisms, *priming of pop-out* (Maljkovic and Nakayama, 1994, 1996), and *contextual cueing* (Chun and Jiang, 1998). Priming of pop-out is thought to be a transient mechanism that uses implicit traces of previously attended features or locations to help guide attention and eye movements. Contextual cueing refers to the fact that previously viewed distractor layouts can speed later target responses when the distractor arrays are repeated. This is true as long as the distractor layouts contain invariant configurations that are predictive of target location. Importantly, for both priming of pop-out and contextual cueing, control experiments have demonstrated that observers have no explicit access to the perceptual information that is guiding their behavior.

Behavioral evidence for implicit detection of change

In line with general claims for implicit perceptual effects, several recent studies have begun to examine whether *change* could also be registered in the absence of awareness. Recently, we have used simplified change blindness displays, such as those shown in Fig. 3, to explore both the implicit localization and identification of change (Fernandez-Duque and Thornton, 2000; Thornton and Fernandez-Duque, 2000).

Observers were shown arrays containing 8, 12, or 16 rectangles (half horizontal, half vertical). An array was displayed for 250 ms, after which the screen went blank for 250 ms, then the array reappeared with one of the items in a new orientation, having rotated about its center by 90°.

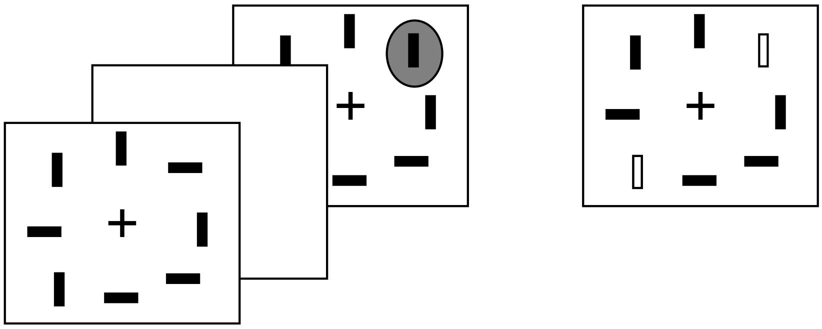
In one series of studies (Fernandez-Duque and Thornton, 2000), the second display of the array was ?#2 followed (after a 250 ms delay) by a 2AFC task in which two items were highlighted, the item that changed and a diametrically opposite distractor item. Observers were required to indicate which of the two items they thought had changed. If they were aware of the change, this would be an easy decision. If they had no awareness, they were instructed to guess. Following the localization response, observers indicated whether they had seen the item change. The interesting finding was that even in the absence of awareness, observers consistently performed above chance in this 2AFC localization task.

Interestingly, in control experiments we attempted to ascertain the contribution of attention to this implicit localization effect by pairing the same simplified flicker display to various forms of cueing paradigms. Instead of attempting to localize the change, observers simply responded to a target item which was placed either at the location of change or at the location of the diametrically opposite item. While standard cueing effects were found for changes that were explicitly detected, we found no evidence of attentional costs or benefits when observers were unaware of the change, leading us to conclude that a reorienting of the attentional focus was not involved in this form of implicit change detection.

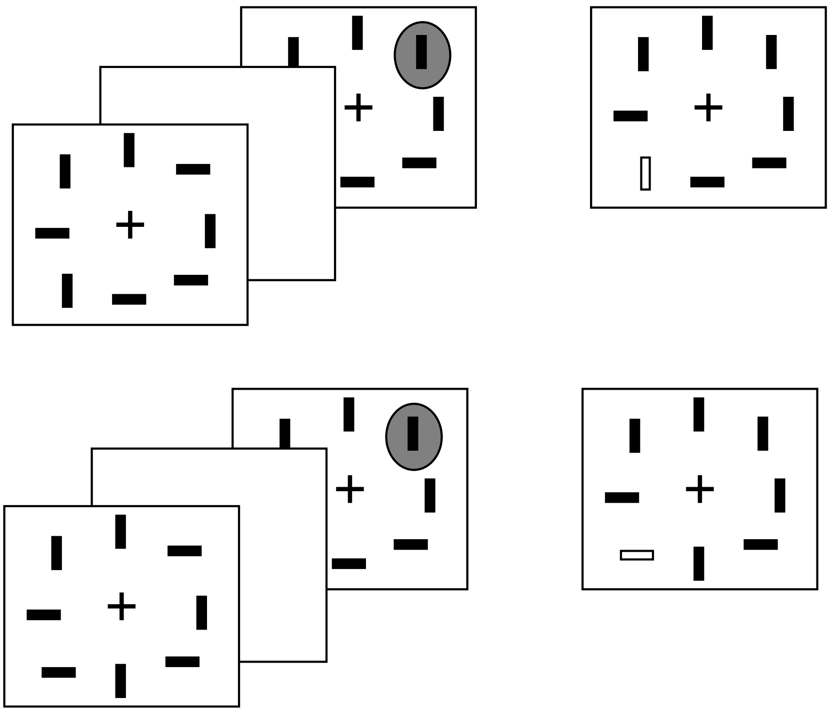
In another series of studies (Thornton and Fernandez-Duque, 2000), we paired rectangle change displays with a speeded orientation discrimination task. The idea here was to explore congruency effects between the changed item and the subsequent probe item, as a function of awareness. Observers were presented with a ring of eight rectangles that appeared briefly, was replaced by a blank screen, and then reappeared. On change trials (66%), one of the items changed orientation between the first and second presentations, say from horizontal to vertical. This change constituted the ‘prime phase’ for the congruency task, where the salience of the final orientation, vertical, would be raised.

Following the change sequence one of the rectangles in the ring was highlighted and observers were instructed to make a speeded response based on this ‘probe’ item’s orientation. We found that for trials in which observers were aware of the change, probes with an orientation incongruent to the changed item were reported more slowly and less accurately than congruent probes. When observers were unaware of the change, their speed of response was identical to the catch trials, suggesting that the change had not been registered. However, a robust congruency effect was still present in the error rates, suggesting that undetected change had primed the appropriate orientation and that this priming then influenced the response to subsequent probes.

Smilek et al. (2000) used a different approach to explore the impact of implicitly detected changes. They combined the flicker paradigm with a standard visual search task (see also Rensink, 2000b). Observers were asked to search through displays of digits to detect the one item that was changing identity across the blank interval. Individual digits were created by turning the elements of an 8-segment array on and off. Large and small changes were cre-



a) Implicit Localization Task



b) Implicit Identification Task

Fig. 3. The studies of the implicit localization and identification reported by Fernandez-Duque and Thornton (2000) and Thornton and Fernandez-Duque (2000) used simplified change detection paradigms coupled with a secondary task. In the initial portion of each trial, shown on the left, the two rectangle frames were identical except for a single object which changed orientation during the blank interstimulus interval (ISI). Change was equiprobable at any location and here involves the rectangle located between 12 and 3 o'clock. The gray oval is added here for illustrative purposes and was not present during experiments. (a) In localization studies, this initial portion of the trial was followed by a probe display in which two items, the changed rectangle and its diametrically opposite partner, were highlighted. Observers were asked to click on the item they thought had changed. (b) In identification studies, the change display was followed by the highlighting of a single probe item to which observers made a speeded orientation response. The critical trials, shown here, were when the probe item was opposite the change location and, its orientation was either congruent with or incongruent with the final orientation of the changed item.

ated by varying the number of elements that were switched on or off during the blank. For example, a large change could be a 2 alternative with a 4 (a change involving 5 elements) and a small change could be a 2 alternating with an 8 (2 elements).

Smilek et al. (2000) measured the efficiency with which large and small changes were found by examining the target present search slopes. They found that the slopes for larger changes were consistently shallower. As the observers' expectations and the nature of the distractors were identical across both types of trial, they concluded that the as-yet-undetected changes were able to guide focal attention to their location. Thus, some form of non-attentional registration of change may have been guiding attention. The suggestion that attention can be implicitly guided to the location of the change contrasts with the results of Fernandez-Duque and Thornton (2000) in which evidence was found for implicit localization of change, but these effects did not appear to be mediated by a covert orienting toward the undetected change. One factor that may account for these different results is the duration of the mask, which was considerably longer in Fernandez-Duque and Thornton (2000) than in the studies by Smilek et al. (2000). In line with this suggestion, Smilek et al. (2002) replicated and extended their original findings, but also revealed that the effect was critically dependent on the duration of the blank. Specifically, when the duration of the blank period was increased from 80 ms to 300 ms, the effect disappeared.

Driver et al. (2001) report two studies from their group which also seem to provide evidence for the implicit processing of change. In one study (Turatto, Russell and Driver, unpubl. data) observers were presented with a simplified flicker display and were asked to report changes in luminance which could occur either within a set of target dots or within a set of background stripes. In some conditions, the well known simultaneous contrast illusion (see Palmer, 1999) was used to create a situation in which a large physical change to the background luminance — alternate stripes changed from light gray to dark gray or vice versa — caused a small illusory change in the luminance of one of the target dots. Observers consistently failed to report the large background change but did sometimes report the illusory change to the target dot. As the illusory dot change completely depended on the background change, this suggests that the unreported modulation of the background stripes was being processed at some level in the visual system.

In another study (Driver, Russell and Howlett, unpubl. data), observers were asked to judge whether two sequentially presented random square patterns were the same or different. In addition to the target patterns, each display also contained a background pattern of dots, which could be organized into regular columns/rows or could have a random organization. The crucial manipulation was that on some trials the organization of the background dots remained constant across the two presentations of the target pattern and on some trials it changed. While a surprise retrospective question, as used in studies of inattentional blindness (Mack et al., 1992; see below), indicated that observers could not explicitly report changes to the organization of the background, both the speed and accuracy of the central task were affected by that organization. Specifically, target-different responses were faster and more accurate when the background also changed and target-same responses were faster and more accurate when the background did not change.

Williams and Simons (2000) used response time measures to identify another example of implicit detection. On each trial of their study, observers were asked to detect feature changes to one of a family of novel complex objects called Fribbles (Williams, 1997). On each trial a single object was briefly shown, occluded and then redisplayed with 0, 1, 2, or 3 of its features modified. Even though only a single object was present on each trial, observers were generally quite poor at reporting changes, with performance generally increasing as a function of the number of changed features. Williams and Simons (2000) also noted, however, that the speed with which observers responded 'same' (i.e., that no change had occurred) varied depending on whether a physical change had taken place. That is, even when observers did not explicitly notice the change, it appeared to implicitly affect another aspect of their behavior, speed of response. Williams and Simons (2000) suggested that such implicit effects might arise simply because explicit reports are a less sensitive measure of change registration than other behavioral consequences.

Two other phenomena closely related to change blindness are worthy of mention in this section, as both have provided evidence for implicit effects involving a spatiotemporal component. In studies of inattentional blindness (Mack et al., 1992; Rock et al., 1992; Mack and Rock, 1998) observers are asked to perform an attentionally demanding primary task — for example, judging the length of two similar line segments — for an extended period of time. On a critical trial, a suprathreshold change is made to the background of the display. For example, random dot patterns may become grouped in some way (Mack et al., 1992), or completely new items, such as dot patterns (Moore and Egeth, 1997) or connecting contours (Chen, 1998) may be added. Even though the unexpected event completely changes the overall display, observers are very often unaware of it and appear to have no explicit access to the nature of the change.

Nevertheless, several studies have now shown that these undetected changes are registered by the visual system and can affect subsequent behavior. For example, Moore and Egeth (1997) introduced flanking patterns to the background of their displays which evoked either the Ponzo illusion or the Müller–Lyer illusion. Both of the these manipulations affected behavior on the primary task, line length judgement, even though the changes were rarely explicitly reported. Similarly, Chen (1998) had observers make size discrimination judgements and then introduced additional features on a critical trial. Very few observers were able to explicitly report the change to the display; however, response times on the primary task were significantly slower when the change was present.

The unexpected events introduced in these studies undoubtedly produce a transient change to the nature of an ongoing display, and thus the failure to report such events is a form of change blindness. As the traditional interpretation of inattentional blindness assumes that such failures arise due to a lack of attention, the implicit effects described by Moore and Egeth (1997) and Chen (1998) are perhaps best attributed to the non-attentional stream shown in Fig. 2. However, as also shown in Fig. 2, and as noted above, a lack of awareness may not always equal a lack of attention during the registration of a change. Further studies will be needed to more clearly determine the origin of these effects.

Another paradigm to show behavioral consequences of change other than explicit *visual* awareness is what Rensink (2002b) has termed ‘mindsight’. This involves a standard flicker paradigm and two explicit responses. In addition to indicating when a change has been ‘seen’, observers were also asked to indicate when they can first ‘sense’ the presence of a change. Patterns of reaction times indicated that a subset of observers could reliably sense the presence of a change — where sensing can be thought of as conscious, non-visual awareness — several seconds before they were visually aware of the change. Rensink (2002b) suggests that sensing and seeing are qualitatively distinct processes, with only the latter relying directly on focused attention.

The need for converging evidence

As the previous section demonstrates, there are now several lines of independent behavioral evidence to support the notion that change can be represented outside of awareness. However, some studies have failed to show implicit representation of change. Those findings are important in the current context because they help define the necessary conditions for implicit representation of change.

For example, unpublished studies from our lab found no evidence of implicit localization when attention was focused away from the changing array on a demanding secondary task. Similarly, when observers have the opportunity to actively search, using their eyes to scan through a complex display with multiple flickers, no implicit localization effects were found (Mitroff and Simons, 2002). These findings could be reconciled under a proposal that some level of *distributed attention* is needed for implicit localization of change. This proposal makes the prediction that implicit localization of change should be evident when attention is distributed over the whole display but not when attention is being focused *away* from the change onto other display details. One way to explore this prediction, and more generally to resolve conflicting behavioral findings, would be to seek converging evidence from other methodologies (e.g., eye movement studies or neuroimaging).

Another motivation for moving beyond strictly behavioral paradigms relates to the generally agreed importance (and difficulty) of ruling out the contribution of explicit processes when making claims about potential implicit effects (Reingold and Merikle, 1990). Such concerns have given rise to a lively debate about the existence of implicit representation of change.

For example, in the study by Smilek et al. (2000) which was described in the previous section, large changes lead to shallower search slopes than smaller changes. This finding was originally interpreted as suggesting that attention was guided to the location of large changes more effectively than to the location of the small changes. More recently, this interpretation has been challenged on the grounds that slope differences may stem from increased difficulty in detecting small changes (Mitroff et al., 2002). According to this alternative interpretation, the size of change is not a factor in guiding attention. Instead, attention is allocated to every item with equal probability, but attended items with a small change are more likely to be missed than attended items with a large change. Such misses lead to disproportionately slow search times, and in this way disproportionately increase the duration of search for small changes.

This alternative proposal is compelling in that it explains the original findings by Smilek et al. (2000). However, it is challenged by follow-up studies showing that the advantage for large changes depends on the duration of the global mask (Smilek et al., 2002). More specifically, when the duration of the mask is increased from 80 ms to 300 ms, the bias toward large changes disappears. An account based on small changes being missed more often than large changes would need to pose different target detection mechanisms for short and long intervals. Indeed, some researchers have adopted this approach, arguing that longer durations favor object-based processing while short durations favor feature-based processing (Richards et al., 2001).

The findings of Smilek et al. (2000) also depend on spatial proximity. When the displays are presented side-by-side, increasing the spatial disparity, large changes do not benefit relative to small changes (Smilek et al., 2002). This finding again poses a challenge to interpretations based on the small changes being missed more often than large changes as it is not clear why such mechanisms would apply only to the flicker paradigm, and not to the side-by-side paradigm.

Mitroff et al. (2002) also raised concerns about the interpretation of the reaction time data of Williams and Simons (2000). Here ‘same’ responses on undetected change trials had been slower than ‘same’ responses on catch trials when no physical change had occurred. Rather than reflecting an independent implicit effect, Mitroff et al., suggest that slower response times could be an indication of lower confidence, which in turn reflects explicit detection. In line with this suggestion, in a control experiment which replicated the main finding of Williams and Simons (2000), a weak positive correlation ($r = 0.282$) was found between speed of response and confidence. Nevertheless, an explanation of speed differences based on reduced confidence in explicit reports rests on the further assumption that implicit detection of change has no influence on subjects’ level of confidence. The resolution of this issue would require a clearer understanding of the relationship between awareness and confidence in the context of change.

Claims for the implicit localization (Fernandez-Duque and Thornton, 2000) and identification (Thornton and Fernandez-Duque, 2000) of change have also been questioned. Mitroff et al. (2002) have suggested that these reports of implicit processing can be explained by explicit mechanisms. Elsewhere, we discuss in detail why these specific criticisms do not appear to be justified (Fernandez-Duque and Thornton, 2002). However, such criticisms highlight the difficulty in providing irrefutable behavioral evidence for implicit processing of change. That is, although it is possible to define criteria for establishing indisputable implicit measures (e.g., Holender, 1986; Reingold and Merikle, 1990), and some researchers have adopted them in the context of change detection (Mitroff et al., 2002; Simons and Silverman, 2002), such criteria are often so strict that they place an almost undue of proof on the researcher given the realistic constraints of most experimental scenarios.

A more productive approach involves the realization that any single methodology is unlikely to provide irrefutable evidence. Instead, we should seek converging evidence from multiple methodologies, accepting that each individual approach has its strengths and weaknesses. In this way we may be able to develop criteria that are still conservative enough to minimize false discoveries while at the same time ensuring that genuinely new phenomena are not impossible to establish. In the remainder of this chapter, we review several existing lines of evidence that, when combined with behavioral findings, may provide us with useful, practical tools for exploring the implicit detection of change.

Evidence from eye movement studies

The use of eye movement patterns to study aspects of changing displays considerably pre-dates the current interest in change detection and change blindness (e.g., Bridgeman et al., 1975; McConkie and Zola, 1979). In particular, the question of information processing before, during and after saccadic eye movements has generated a great deal of research (see Verfaillie and De Graef, 2001 for an overview). It has been well-established that while the eye is making its frequent (e.g., 3–4 per second) short (e.g., 40 ms), rapid (up to 1000°/s) saccadic movements during natural viewing, no information uptake is possible (e.g., Matin, 1974). We thus acquire visual information about the world during pre- and post-saccadic fixations. What has been less clear is the extent to which information from pre- and post-saccadic information can be integrated. To help answer this question researchers began to study saccade-contingent changes.

Saccade-contingent changes are display alterations that are triggered by the detection of high-velocity eye movements. Much of the earlier work on saccade-contingent changes involved alterations to written texts during reading (e.g., McConkie and Zola, 1979; Pollatsek and Rayner, 1992), displacement detection in simple displays (e.g., Bridgeman et al., 1975; Li and Matin, 1990) or the integration of information in random visual patterns (e.g., Irwin et al., 1983). The general finding from this early work was that saccade-contingent changes were rarely noticed and thus it was concluded that little or no integration takes place.

More recent investigations of transsaccadic object and scene memory have favored the use of natural scenes. These studies also find that transsaccadic changes are sometimes very hard to detect (e.g., Grimes, 1996; McConkie and Currie, 1996; Hollingworth and Henderson, 2002). However, there is less agreement on whether this necessarily implies a general lack of integration. Some researchers have claimed complete integration of pre- and post-saccadic views (e.g., McConkie and Rayner, 1976; Feldman, 1985) while others have argued for the complete absence of such transsaccadic integration (e.g., O'Regan, 1992). Most likely, the truth lies somewhere in between, with some information being maintained across views, but only if it is 'selected and coded' in a certain way (Verfaillie and De Graef, 2001). Selection appears to depend on a number of factors including the particular demands of the task (Ballard et al., 1998; Hayhoe et al., 1998; Land et al., 1999) and the nature of the stimulus (Pollatsek and Rayner, 2001; Gysen et al., 2002). Coding appears to involve some form of consolidation from sensory representations into more stable short-term (e.g., Irwin and Andrews, 1996) or long-term memory representations (e.g., Hollingworth and Henderson, 2002).

The techniques developed for studying transsaccadic changes are very useful in the context of implicit change detection as they provide a useful alternative to simply asking observers what they saw. More specifically, examination of fixation frequency, duration and overall patterning can be used to infer whether unreported changes nevertheless had some impact on the visual system.

Hollingworth et al. (2001a,b), for example, asked observers to examine line drawings of complex, naturalistic scenes for a later memory test. Observers were also told that changes might be introduced to the scenes as they were scanning them and that they should immediately report any detected changes by pressing a key. On critical trials, objects were replaced as the eyes moved away from them. When the eyes returned to a changed object after several seconds, fixation durations were consistently longer (749 ms) than when no change was made to the object (499 ms), even in the absence of explicit detection.

Similar implicit effects on fixation duration have been found in other studies (e.g., Hayhoe et al., 1998; Henderson and Hollingworth, 2002; Hollingworth and Henderson, 2002). The study of Hayhoe et al., is particularly interesting for at least two reasons. First, not only the fixation duration, but the frequency of saccades was affected by the undetected changes. Second, changes only occurred on a small number of trails (10%) and observers were engaged in a demanding primary task (block copying), factors that minimize the use of explicit strategies.

While the previous two studies reveal implicit processing of change within a short time interval, other eye movement studies have shown that changes can be implicitly detected even when an interval of several minutes is presented between the pre- and post-change scene (Ryan et al., 2000). In this experiment, subjects saw a series of complex scenes twice. When presented for the second time, each scene could be either an exact repetition or a modified version of the original scene. Normal subjects revealed increased viewing of the changed region, even when unaware of the change, a finding that provides convergent support for implicit representation of change, in this case over a longer period of time.

The studies reviewed in this section demonstrate that eye movement patterns can provide a more sensitive measure of change registration than verbal reports. Future studies will have to address whether these implicit effects originate in separate, non-attentional mechanisms, or depend on below-threshold attentional registration (see Fig. 2).

Evidence from motor control

There has been considerable debate in the literature as to whether perception and action share common representational mechanisms. Some researchers have proposed a clear separation of processing (e.g., Goodale, 1993; Milner and Goodale, 1995), while others have suggested that they share a 'common code' (e.g., Hommel et al., 2001). Of interest here, are claims that perception and action might sometimes be differentially affected by visual illusions and display manipulations. For example, Aglioti et al. (1995) and Brenner and Smeets (1996) suggested that grasping movements might be immune, respectively, to the Ebbinghaus (or Tichener) illusion and the Ponzo illusion, both of which lead to large perceptual distortions (but see Franz et al., 2000, 2001 for conflicting evidence). Abrams and Landgraf (1990) showed how distance estimates (thought to involve perceptual/cognitive planning) could be affected by an induced motion illusion while location estimates (more related to action) were not.

While the proposed dissociation between perception and action representations remains controversial, it may still prove useful to explore within the context of change detection. This is particularly true in the light of patient work suggesting accurate behavioral responses in the absence of conscious awareness, either to the presence of an object (e.g., blindsight, Weiskrantz, 1986; Cowey and Stoerig, 1991) or to the action typically associated with an object (e.g., some forms of agnosia, Goodale and Milner, 1992).

Of course, the eye movement studies reviewed above clearly relate to motor control. More directly, a number of researchers have suggested at least a temporal dissociation between manual responses to a change and conscious awareness of the change. For instance, when the size or location of a rod is changed as an observer attempts to grasp it, manual adjustments occur several hundred milliseconds before observers can indicate awareness of the change with a verbal report (Castiello et al., 1991; Castiello and Jeannerod, 1991). Importantly, control experiments showed that these effects did not arise due to inherent differences in speed between the two methods of responding (Castiello et al., 1991).

More directly, several studies have demonstrated motor sensitivity to change in the complete absence of explicit report. For example, Bridgeman et al. (1979) and Goodale et al. (1986) both showed that pointing movements towards a target were often corrected when the position of an object was changed during a saccade, even though observers were unaware of the change. More recently, Repp (2000) has used perceptual–motor synchronization tasks to demonstrate implicit detection of change. In these tasks observers were required to press a key in response to a sequence of auditory tones. Repp found that subliminal changes to the timing of the tone sequence, that is, variations "that were well below the explicit detection threshold", nevertheless "led to effective adjustments in the timing of the motor response" (Repp, 2000; see also Thaut et al., 1998; Koch, 1999; Repp, 2001).

Cognitive neuroscience

Since the 1980s there has been a steady increase in the number of brain imaging techniques that have become available for helping to explore the nature of mental processes. The field of Cognitive

Neuroscience (see Gazzaniga et al., 2000 for an introduction), evolved largely in response to these innovations and aims to bring together various disciplines, including neurology, psychology, physiology and imaging.

While there has been a great surge in the number of behavioral studies relating to change blindness over the last 5 years, there are still relatively few that have taken a cognitive neuroscience approach. In this section, we review those imaging studies and also discuss what might be learned from examining relevant patient populations. Imaging, in particular, has the potential to reveal measures of implicit change and to track the formation of 'registered' changes, even if they lack measurable behavioral consequences (see Fig. 2).

Functional magnetic resonance imaging (fMRI)

Functional magnetic resonance imaging (fMRI) is a technique that relies on monitoring patterns of blood flow associated with neural activity. As the magnetic properties of blood changes as a function of oxygenation levels, it is possible to distinguish areas which are receiving fresh, oxygenated blood, — due to metabolic activity in response to some 'functional' stimuli — from those whose activity level is stable. As changes in blood flow occur over the course of seconds, rather than milliseconds, fMRI is a good technique for establishing the locus of neural mechanisms but less useful for establishing the time course of such activity.

Huettel et al. (2001) provide an initial picture of the various processes associated with change detection using a flicker paradigm very similar to that originally employed by Rensink et al. (1997). Post-hoc event-related analysis was used to divide patterns of activation into three task-related categories: transient responses to the flickering stimuli, sustained activation related to the visual search for change, and transient responses due to target detection.

Stimulus-dependent transient responses to flicker onset/offset were found mainly in primary visual areas. Sustained activations were found in areas known participate in visual search and spatial orienting, including intraparietal sulcus, and frontal and supplementary eye fields. This type of responses declined following target detection. As observers were free to move their eyes during this task, such patterns of activation could have been driven due to the attentional demands of the task or, more directly, by the overt eye movements known to be closely associated with them (e.g., Andersen et al., 1992; Corbetta, 1998). Finally, the transient activation associated with the identification of the change involved several areas known to be associated with target detection (e.g., anterior cingulate) and response execution (e.g., basal ganglia and cerebellum).

Huettel et al.'s study demonstrates how an ongoing search process, such as those required in the flicker paradigm, can be decomposed into components previously identified in short-duration visual attention tasks. However, their study was not designed to probe differences between change detection and change blindness.

Beck et al. (2001) used fMRI to directly examine such differences. They combined a simplified flicker paradigm with an attentionally demanding baseline letter detection task. The change detection task involved reporting a change in two peripherally presented images of either faces or houses, which were flickered for only two cycles. The difficulty of the letter detection task was adapted for each observer to ensure that a roughly equal number of changes were missed as were detected.

As the main goal of Beck et al.'s study was to explore the brain regions that might differentiate change detection from change blindness, their main comparison was between trials in which a change was detected and trials in which the change was missed. Conscious detection of change led to activation of separate category-specific ventral regions (Kanwisher et al., 1997; Epstein and Kanwisher, 1998), as well as a common network of dorsal frontoparietal areas.

More importantly, for some subjects, the pattern of activation for undetected changes was different from the pattern of activation in trials with no change. This result suggests that unreported changes were processed by the visual system. Furthermore, the loci of activation for these unreported changes did not overlap with the areas active during conscious change detection, consistent with the hypothesis of separate mechanisms for implicit and explicit detection of change. However, a more definitive answer must await further research, as in this study activations by implicit changes were only present in a subset of subjects (6 out of 10) for one type of stimulus (faces).

Event-related potentials (ERPs)

Neural activity in large populations of cells gives rise to electrical potentials that can be detected by electrodes placed on the surface of the scalp. Event-related potentials (ERPs) are waveforms associated with a particular task that can be extracted from the overall pattern of neural activity by averaging across multiple trials. The main strength of ERPs is their excellent temporal resolution, which allows them to distinguish two events occurring 4 ms apart. This temporal resolution allows scientists to inquire about the stage of information processing at which attentional effects first occur and offers the possibility of determining when (i.e., how long after the stimulus onset) implicit and explicit processes first diverge.

Niedeggen et al. (2001) used ERPs to explore the detection of a single changing item (position change or identity change) in arrays of alphanumeric characters which were flickered for up to five cycles. The main finding of this study was that target detection was accompanied by a large positive deflection in the 200–800 ms range which was most pronounced over central and parietal sites. This waveform, known as the P3, is a well established finding in the ERP literature (for a review, see Donchin and Coles, 1988). It typically accompanies the conscious detection of low-probability targets (Johnson, 1986) and is thought to reflect a range of cognitive processes, including the updating of working memory, the making of binary decision, as well as various forms of recognition and identification judgements (Donchin and Coles, 1988).

A more interesting finding comes from the trials preceding the detection of the change. In those trials, there is an effect of similar distribution but smaller in magnitude than the target detection effect. It is possible that this effect stems from some implicit detection of change, which precedes the explicit detection. Indeed, this effect might help to interpret a finding by Mitroff and Simons (2002) that when implicit localization responses are required on each successive image in a flicker paradigm, performance only improves in the image immediately preceding detection. However, other interpretations need to be ruled out first. It is possible that detected changes sometimes go unreported because the subject waits until the next cycle for confirmation. Similarly, the effects may reflect a lack of confidence on the detection, a possibility that receives support from studies showing that magnitude of the P3 component increases with increased confidence (Hillyard et al., 1971).

Niedeggen et al. (2001) also looked directly for indications of implicit change detection by comparing waveforms from trials in which a change was present but was not reported to those in which a change was absent, the catch trials. They were unable to establish any difference between these two types of trial, suggesting that implicit mechanisms were not operating. However, it is unclear whether such a design has enough power to detect possible implicit effects, given that there were only about 15% of trials with undetected change. Furthermore, subjects in this task were allowed to move their eyes freely. This, combined with the quite long stimulus displays (1500 ms) may have masked implicit effects as ERPs are exquisitely sensitive to eye movements, and in the presence of eye movements, other signals are often hard to detect.

Markers for implicit representation of change were found in a second ERP study that used a flicker paradigm with complex scenes and required subjects to keep eyes fixating at the center of the screen (Fernandez-Duque et al., 2002). In this task, a within-trial design was used in which a change appeared and disappeared during different phases of each trial, and observers performed several tasks designed to control the distribution of attention. The design ensured that each trial contained periods in which the observer was unaware of change and then later became aware of the change, consciously attending to the change for several seconds after detection. Additionally, task demands ensured that attention was sometimes focused at the change location and sometimes distributed across the whole display.

The analysis proceeded in the following manner. First, markers associated with focusing attention in the absence of a change were identified. Relative to active search, focusing attention in the absence of a change enhanced an ERP-negative component over frontal sites around 100–300 ms after stimulus onset, and in posterior sites at the 150–300 ms window. These effects were then compared to markers elicited by an explicit awareness of change. Being aware of a change replicated the attentional effects in frontal and posterior sites. This is to be expected, as awareness of change depends on focusing attention at the location of change. More importantly, being aware of a change also produced a unique positive deflection in the 350–600 ms window, broadly distributed with its epicenter in medio-central areas. The unique topography and time course of this latter modulation, together with its dependence on the aware perception of change, distinguishes this 'awareness of change' electrophysiological response from the electrophysiological effects of focused attention.

Of more interest to the current topic, was a comparison between phases in which a change was present and the subject was unaware, relative to the stage in which a subject was looking for an absent change. This comparison revealed that undetected changes were accompanied by a bilateral positive deflection in anterior sites which reached significance at 240 ms and remained significant until 300 ms. Interestingly, both the time course and the topography of this deflection were different from those associated with focused attention or awareness. If this deflection proves to be an 'implicit marker' of change — as opposed to a reflection of incidental explicit or strategic processing — then these differences in time course and topography suggest that implicitly detected changes may be registered by different neural systems than those responsible for explicitly detected changes.

Change blindness in special populations

Recently, researchers have started to use change blindness paradigms to explore attention and memory processes in special populations.

In one study, Harp and Rensink (1999) compared the ability of older and younger adults to perform visual search for change (Rensink, 2000b). They found that while older adults were able to filter out irrelevant stimuli just as effectively as younger adults, there was a general slow down in the speed of attention with increasing age. Consistent with this finding, Pringle et al. (2001) found that older adults took longer to detect changes than young subjects. They suggest that this reduced ability to detect changes may be attributable in part to a narrowing of attentional breadth. As both of these studies only probed explicit detection, it may be informative to examine whether aging is also accompanied by a similar decline in the implicit detection of change.

Neglect patients, who have severe problems in spatial attention, may be a special population particularly suited for exploring implicit and explicit representation of change. It has been well established that neglect patients process physical, semantic, and emotional information of objects presented to their neglected field, for which they lack subjective awareness. It is not known whether information about changes would also be encoded without awareness in the neglect field, and studies of that kind may reveal a lot about the role of spatial attention in the representation of change.

Studies with special populations could be informative not only about the role of attention in the representation of change, but also about the role of memory in holding those representations. For example, one recent study has used eye movement methodology to explore implicit and explicit detection of change in amnesic patients (Ryan et al., 2000). Both amnesic patients and normal adults saw a series of complex scenes twice. When presented for the second time, each scene could be either an exact repetition or a modified version of the original scene. Normal subjects revealed increased viewing of the changed region, even when unaware of the change, a finding that provides convergent support for implicit representation of change. Interestingly, amnesic patients did not show such an effect, providing evidence of their failure in relational memory.

Conclusions

In this chapter we have explored the notion of *implicit change detection*. We suggest that when an observer fails to explicitly report a change, such events may still sometimes be registered by the visual system and, furthermore, influence subsequent behavior. Two key theoretical issues relating to this possibility concern the role of attention in creating spatiotemporally coherent representations and the relationship between attention and awareness. In the framework described in Fig. 2, we raised the theoretical possibility that change may be represented both with and without the aid of attention, and that the role of attention in modulating awareness is at least partially independent from questions of representation. Several empirical studies have provided evidence that behavioral consequences other than aware detection can accompany the presence of a change. While such behavioral studies are a useful starting point, we argue that it is only by seeking converging evidence from a range of other methodologies, such as eye movements, neuroimaging, and patient populations, that a clear picture will emerge. Here, we have reviewed the current state of the art in this ongoing, interdisciplinary research effort, and have outlined some possible new directions.

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QUERIES:

?#1: ..had be extracted..: had to be/had been/ (page 104)
?#2: Please define 2AFC (page 105)
?#3: The following references have not been referred to in the text: Ball et al., 1988; Carr and Dagenbach, 1990; DeJong et al., 1994; Henderson and Hollingworth, 1999; Humphreys and Kramer, 1997; Neely, 1977; Pelli and Zhang, 1991; Rensink, 1990; Rogers and Fisk, 1991; and Stroop, 1992 (page 115)
?#4: Check page numbers. (page 115)
?#5: Submitted to which journal? (page 116)
?#6: Update? (page 116)
?#7: Cogn. Neuropsychol(ogy)? (page 116)
?#8: Still under review? Submitted to which journal? See also refs. Henderson/Hollingworth; Hollingworth; Smilek et al. (page 116)
?#9: Update? (page 116)
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