J. Hyönä, D.P. Munoz, W. Heide and R. Radach (Eds.)
Progress in Brain Research, Vol. 140

CHAPTER 13

Changes

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> "All things change, and nothing stays still. . . " (Heraclitus, c. 500 BCE)

Introduction

This past decade has seen a great resurgence of interest in the perception of change. Change has, of course, long been recognized as a phenomenon worthy of study, and vision scientists have given their attention to it at various times in the past (for a review, see Rensink, 2002a). But things seem different this time around. This time, there is an emerging belief that instead of being just another visual ability, the perception of change may be something central to our 'visual life', and that the mechanisms that underlie it may provide considerable insight into the operation of much of our visual system.

This development may have been sparked by a number of factors: technology that allowed the easy creation of dynamic displays, a feeling in the air that it was time for something new, or it may have simply been a matter of chance. But once underway, this development was fueled by results, results that included both novel behavioral effects and new theoretical insights. Many of these centered around *change blindness* [1], the failure of observers to see large changes that are made contingent upon some transient event, such as a brief blank, or a saccade (see Rensink, 2000b). Given the strength and robustness of these effects, they provide a powerful way to explore a number of issues, such as the extent to which our behavior is based on nonconscious processing of visual input, the way that attention is (and is not) involved in vision, and the extent to which visual information is accumulated across saccades.

The chapters presented in this section provide excellent illustrations of the success of this approach in providing new insights into the operation of our visual system. In what follows, an attempt will be made to consolidate the results and conclusions obtained by each of these studies with a broader theoretical framework based on earlier work. Such an approach will hopefully show that studies of change perception can help resolve a number of important issues in visual perception, and — even more importantly — raise a number of interesting new questions.

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[1] It should be emphasized that change blindness is a true *blindness* (failure to see the change), and not an *amnesia* (forgetting a change that was perceived). Although observers may have seen the previous display (and so might be amnesic in regard to its contents), the fact that they are set to report change as soon as it occurs makes it impossible that they see the change itself and then forget. For a more detailed discussion of this issue, see Rensink (2000a).

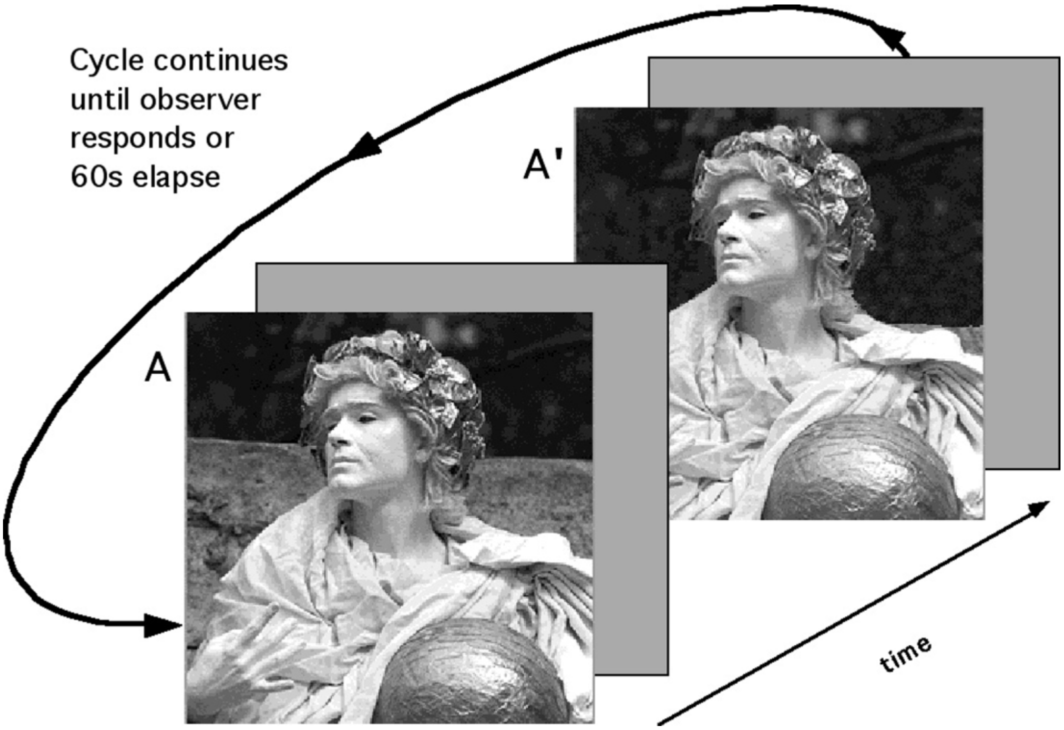

Fig. 1. Flicker paradigm. Original image A (statue with background wall) and modified image A′ (statue with wall lowered) are displayed in the order A, A′, A, A″, . . . with gray fields briefly displayed between successive images (Rensink et al., 1997).

Background

Change blindness

Consider the situation shown in Fig. 1. In this *flicker paradigm*, an original image A alternates with a modified image A′, with brief blank fields between successive images.

Observers have great difficulty noticing most changes under these conditions, even when the changes are large, repeatedly made, and the observer knows they will occur. Such *change blindness* (Rensink et al., 1997) is a very general phenomenon: it can be induced in a variety of ways, such as when changes occur simultaneously with (1) saccades (e.g., Bridgeman et al., 1975); (2) real-world interruptions (Simons and Levin, 1998); (3) brief ‘splats’ that do not cover the change (Rensink et al., 2000). For a comprehensive review of work on change blindness, see Simons (2000) and Rensink (2002a,b).

The need for attention to perceive change

The generality and robustness of this effect indicates that change blindness involves mechanisms central to our visual experience of the world. In particular, it has been suggested that *focused attention is needed for the conscious perception of change* (Rensink et al., 1997). In this view, attention creates a coherent structure that can support the perception of change. If the transient signal that accompanies the change is swamped via other transients (or is otherwise rendered inoperative), the guidance of attention is lost and change blindness is induced.

Coherence theory

Change blindness can be severe, and remains severe even when observers are given several seconds to try to memorize the image (Rensink et al., 2000). To account for this, it has been proposed that the coherent structures formed by attention are not long-lasting,

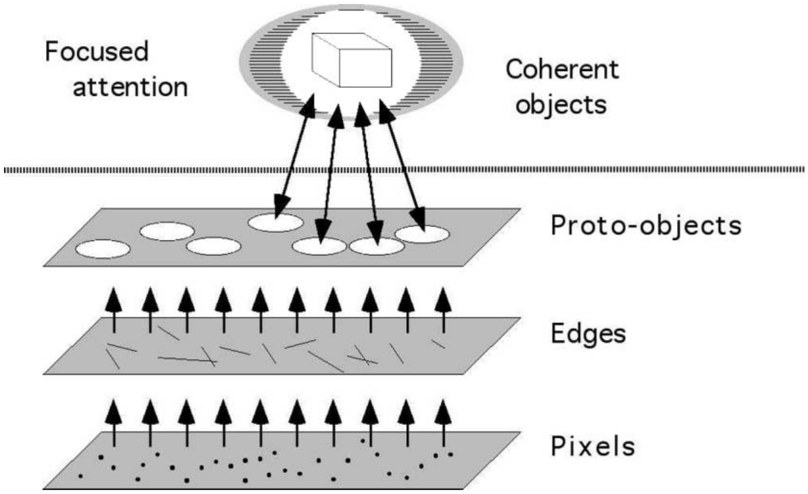

Fig. 2. Coherence theory. Early-level processes create proto-objects rapidly and in parallel across the visual field. Focused attention ‘grabs’ these volatile proto-objects and stabilizes them. As long as the proto-objects are ‘held’ in a coherence field, they form an individuated object with both temporal and spatial coherence (Rensink, 2000c).

but instead exist only as long as attention is directed to them. More precisely, this *coherence theory* of attention (Rensink, 2000c) has three parts (Fig. 2).

(i) Prior to focused attention, low-level *proto-objects* are continually formed rapidly and in parallel across the visual field. These ‘preattentive’ structures can be quite complex, but are volatile, having no real memory. Thus, they are simply *replaced* when any new stimulus appears at their location.

(ii) Focused attention selects a small number of proto-objects and *stabilizes* them. This is done via links that feed back from a single, higher-level *nexus*; the resultant circuit is referred to as a *coherence field*. This representation has a high degree of coherence over space and time: any new stimulus at that location is treated as the *change* of an existing structure rather than the appearance of a new one.

(iii) After focused attention is released, the object loses its coherence and dissolves back into its constituent proto-objects. There is little or no ‘after-effect’ of having been attended.

The limited amount of information that can be attended at any one time explains why observers can fail to detect changes in ‘attended’ objects (Levin and Simons, 1997). When focused attention is directed to something in the world, it will not generally be possible to represent all of its properties in a coherence field-only a few of its aspects can be represented at any one time. If an aspect being represented is one of the aspects changing in the world, the change will be seen; otherwise, change blindness will again result.

Triadic architecture

Given that attention is limited, it is critical that eye movements and attentional shifts be made to the appropriate object at the appropriate time. One proposal for how this might be carried out is the *triadic architecture* of visual processing (Rensink, 2000c). This is composed with three largely independent systems (Fig. 3):

(i) a high-capacity early-level system that rapidly creates detailed, volatile proto-objects in parallel across the visual field;

(ii) a limited-capacity attentional system that forms these structures into representations of objects with spatiotemporal coherence;

(iii) a limited-capacity nonattentional system that provides a context (or *setting*) to guide attention to the appropriate objects in the scene.

According to this view, a complete representation of the scene is never constructed: only one coherent object is represented at any one time, with the setting providing a context that successfully directs attention so that the right information is made available at the right time. Such an approach uses representations that are stable and representations that contain large

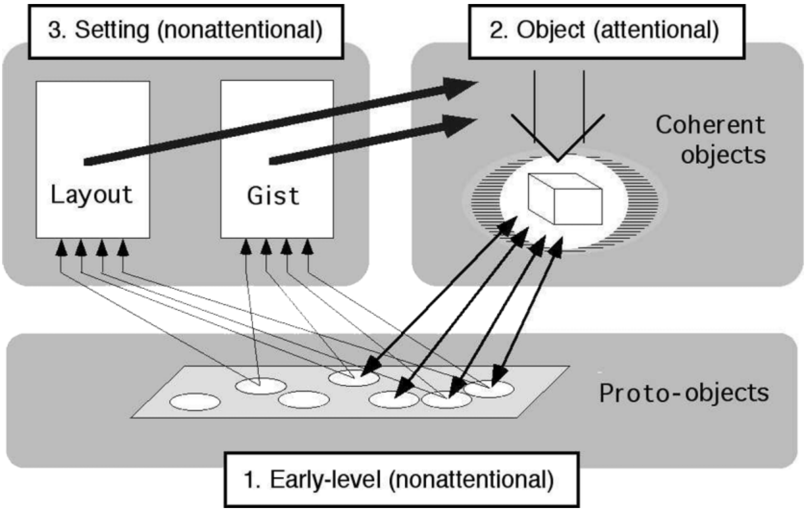

Fig. 3. Triadic architecture. Visual perception may be carried out via the interaction of three systems. (1) Early-level processes create volatile proto-objects. (2) Focused attention acts as a hand to ‘grab’ these structures and form an object with both temporal and spatial coherence. (3) Setting information — obtained via a nonattentional stream — guides the allocation of focused attention (Rensink, 2000c, 2001).

amounts of visual detail. But at no point does it use representations that are both stable *and* contain large amounts of detail.

Note that the setting system is subdivided into at least two subsystems, each of which involves a different aspect of scene structure.

(i) The abstract meaning (or *gist*) of a scene, e.g., whether the scene is a harbor, city, or picnic.

(ii) The spatial arrangement (or *layout*) of objects in the scene. Note that although layout information may not be volatile, it is not detailed, with relatively little information stored concerning each item.

However, it is important to mention that nonattentional streams are also possible. The key point in all of this is that the attentional system is only one among many concurrent systems, and that although attention is required for the formation of coherent structure, it is not necessarily a precursor or a partner in the operation of other aspects of visual perception (Rensink, 2000c).

New developments

Implicit perception of change

Given that large changes can take place for extended stretches of time without being (consciously) seen, change blindness can provide a potentially powerful way to investigate whether various aspects of visual processing can occur implicitly, i.e., occur without being accompanied by conscious visual experience. Thornton and Fernandez-Duque (2002) provide a comprehensive survey of the work that has been done on the implicit detection of change, as well as on related results that support their contention that change can be registered in the absence of visual awareness. Among other things, they make clear the difficulties in establishing the existence of implicit perception. However, they argue that this can be done in a reliable way by looking at consistencies in the patterns of results found via different kinds of tests.

Thornton and Fernandez-Duque make a number of distinctions that are worth keeping in mind, such as those between *visual perception* and *visual registration*, and between *attention* and *awareness*. The first of these is based on the increasing tendency to regard *perception* as being limited to the conscious (or at least, non-motoric) aspects of visual processing (cf. Milner and Goodale, 1995; Rensink, 2000c). The term *registration* is therefore a useful way to discuss the visual pickup of information without committing to whether or not the result will be experienced in a conscious way.

It may be important to point out here that even if a change is *registered* (i.e., it has an effect on an organism via visual transmission), this does not imply that it is *represented* as such. For example, an initial view of an object could be placed into long-term memory, and at some time later compared with a new view. From this it might be deduced that a change has occurred. On the other hand, if the new view was simply stored (or combined) with the old, the variability in the resultant representation might weaken the ability of the organism to recognize the object on the next encounter. The change would then be registered, but it would be difficult to say that is represented, at least in any direct way.

Thornton and Fernandez-Duque also make clear the importance of distinguishing between two roles of attention: the *modulation* of awareness (a subjective state) and the *construction* of spatiotemporally coherent representations (Fig. 4). They point out that — conceptually, at least — these are two rather different things. Whether or not they really are correlated is far from certain. One source of confusion is the common belief (mentioned by Thornton and Fernandez-Duque) that if an observer attends to an object, all of its properties would be attended, and thus would be put into coherent form. If this were true, the failure to see changes in attended objects would support the separation of these two aspects. However, as discussed above, this is not the case; a coherence field includes only a selected subset of properties (Rensink, 2000b). Thus, most properties of an attended object would not be in coherent form at any time, and so, would not be seen to change. As such, this leaves unsettled the question of whether modulation and formation are separate processes.

Another distinction worth making in this regard is that between attention as selective *access* and attention as selective *construction* of coherent structure (Rensink, 2002b). Although these two aspects may be part of the same process, it is also possible that they are carried out by separate processes (Fig. 4). If so, this would explain why implicit detection of change would fail when attention is directed elsewhere: although attention-as-construction is not required for implicit perception, visual input still is. Thus, if input to the implicit system is stopped due to

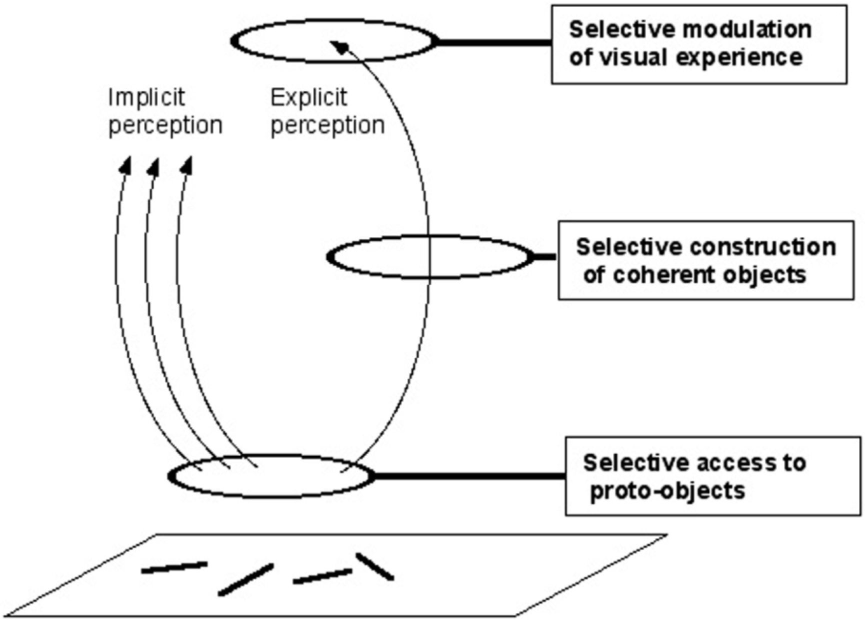

Fig. 4. Possible types of attentional process. Attention (defined as a selective factor that limits processing) can act at least three possible locations. (1) Selective *access* of all processes to the array of early-level proto-objects. (2) Selective *construction* of spatiotemporally coherent representations. (3) Selective *modulation* of conscious awareness. Whether these are aspects of a single process or of different processes remains unknown.

a diversion of attention-as-access, it will effectively stop any implicit perception of change (or any other implicit visual process, for that matter), even if no spatiotemporal coherence is involved.

Applicability of change blindness research

Turning now to the more intensively studied explicit detection of change, Dornhöfer et al. (2002) examine the extent to which change blindness might occur in everyday life, and the extent to which the theoretical conclusions that have been reached would apply to various aspects of vision. Change blindness has already been found to be a surprisingly robust phenomenon (see e.g., Rensink, 2002a): it can, for example, be induced by making changes contingent with brief blank fields (e.g., Rensink et al., 1997), saccades (e.g., Bridgeman et al., 1975), and localized 'splats' that do not cover the item being changed (Rensink et al., 2000). Dornhöfer et al. (2002) compare the degree of change blindness induced via several different methods (blinks, blanks, and saccades), and find that it does not depend on the particular type of method used, nor on the exposure time of the displays. As such, they provide a useful confirmation of the robustness of change blindness, strengthening the argument that it is not due to some experimental artifact, but instead, reflects the failure of mechanisms that are important to everyday vision.

Curiously, after confirming that change blindness is an effect that is both strong and robust, Dornhöfer et al. (2002) argue that we do not need to worry about it much in everyday life, since over 80% of relevant changes were detected. This may not be all the comforting once it is realized that many events (e.g., braking for stopped automobiles ahead) occur many times a day; even one traffic accident a day would be more than most people could endure. More generally, attempting to continually allocate attention to important items is something that is effortful and requires constant vigilance; if anything disturbs this, change blindness could easily result. Indeed, a large number of traffic accidents are caused by drivers engrossed in conversations on their cell phone (e.g., Redelmeier and Tibshirani, 1997), presumably because of attentional diversion.

Following Simons and Levin (1998) and Wallis and Bülthoff (2000), Dornhöfer et al. (2002) also investigate the nature of change perception on dynamic displays. Interestingly, they find differences in performance on static and dynamic displays. These differences are worth further investigation; not only do they occur in situations similar to activities carried out in everyday life (e.g., automobile driving), but they may also provide new insights into the operation of the change-perception process itself.

The dynamics of change perception

As a step towards understanding the dynamics of the representations involved in change perception, Saiki (2002) presents several elegant experiments on the perception of changes in controlled dynamic displays. These are based on a new paradigm (multi-object permanence tracking) that combines aspects of the flicker paradigm (Rensink et al., 1997) with the multiple-object tracking task (Pylyshyn and Storm, 1988); viz., detecting changes in a set of tracked items. (See also Scholl and Pylyshyn, 1998.)

Saiki finds that the ability to detect switches in the properties of these items depends strongly on their velocity, and that the cost of tracking a moving item through space can be separated from the cost of binding its properties to their correct locations. Furthermore, he finds that the tracked items contain only individual features, and not their conjunctions, thereby ruling out the model of *object files* proposed by Kahneman et al. (1992), in which features are bound together in local bundles. Instead, he argues, the mechanism involved in attention is much more like the visual indexes proposed by Ballard et al. (1997) or Pylyshyn and Storm (1988).

Saiki makes no mention of coherence fields, but it is worth examining what implications his results have for this model of attention. As mentioned above (or see Rensink, 2001), a *coherence field* is a circuit formed of feedforward and feedback paths that link a set of (attended) *proto-objects* to a higher-level *nexus*. Whereas the upward propagation of information is relatively straightforward, the downward connections can only be established by a correlation of the nexus signal with that of the proto-object at the target location. (For details on a similar scheme involving a lower-level system of feedforward and feedback connections, see DiLollo et al., 2000.)

Consider now the case where the items are static

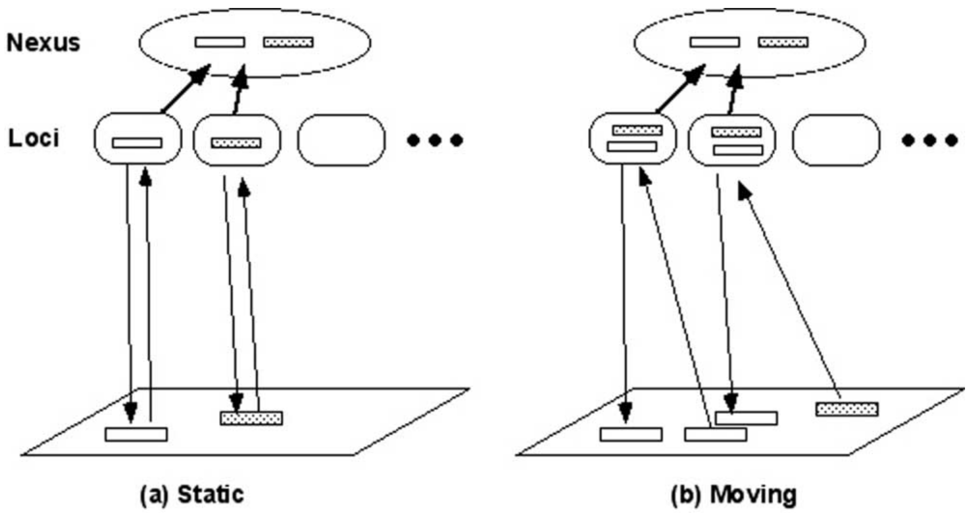

Fig. 5. Dynamics of coherence fields. (a) When proto-objects are static, a feedback circuit (coherence field) is established between a selected proto-object and a locus in the nexus; the contents of these loci are then pooled. (b) When a proto-object is moving, the correlation between the representation at its (actual) position and the representation being sent down the feedback connections deteriorates, since the proto-object is no longer at its expected position. This leads to a delocalization of its spatial linkage, causing the loci to pool properties from several items, and so creating a failure to detect switches among the properties of attended items.

(Fig. 5a). Since a switch of properties between the attended items can be accurately detected, this supports the idea of *weak aggregation* (Rensink, 2001). Here, the nexus has a separate memory *locus* for each link, with the locus signals then combined into an aggregate description. When the items are static, then, a change or switch in any of their properties could be detected. But if the items are moving, a different situation emerges (Fig. 5b): given that the information traveling along the links is propagated at a finite velocity, a moving proto-object would cause problems with correlations between the expected signal (the signal from the nexus) and the signal at the intended location, and these problems would worsen with increasing velocity. Because of the resultant disturbance, the 'locking on' of the downward path would temporarily fail, along with the spatial link. Until spatial localization could be reasserted, each locus would pool signals from a relatively large area of space, thus impeding the ability to detect switches in properties of the (localized) items that were being tracked.

This account is, of course, rather sketchy, and many more experiments will be needed to supply it with more detail (or cause it to be rejected). The important point here, however, is that the experiments of the kind described by Saiki show how dynamic displays can be used to provide important insights into the nature of the coherent representations underlying the conscious perception of change.

Preservation of nonattended information

Although much of the work on explicit change detection has focused on spatiotemporal continuity, Tatler (2002) examines the fate of the other systems involved in visual perception, viz., the array of (unattended) volatile proto-objects in early vision, as well as the various kinds of context information. In particular, he examines the extent to which these can be preserved across saccades. Note that in contrast to an exploration of how well observers can perceive dynamic change[2] (which might be the hallmark of the spatiotemporal coherence associated with focused attention), the tests used by Tatler involve other aspects of visual perception.

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[2] Dynamic change refers to seeing the actual progress of the change itself, and not just seeing that the initial and final states differ. For a more detailed discussion of the various kinds of change that may be distinguished, see Rensink (2002a).

In regard to the elements of early vision, Tatler investigates what can be reported after a saccade is made. His results indicate that the contents of the new fixation overwrite the old, but do not do so immediately. This is consistent with the proposal of Rensink (2000c) that the contents of early vision are volatile, with unattended proto-objects replaced by the proto-objects corresponding to new stimuli appearing at their location. Models of this replacement process based on the phenomenon of common-onset masking (DiLollo et al., 2000) indicate that most of this replacement is achieved by 160 ms, and the remainder by 320 ms. This is reasonably consistent with Tatler's estimate that most of the replacement is achieved by 250 ms, and the remainder by 400 ms.

The conclusions that Tatler draws concerning the nature of this kind of visual memory level are largely consistent with the characteristics of early vision, and is also consistent with the proposal that iconic memory (or *informational persistence*) is just the decaying trace of the proto-object array (Rensink, 2000c). Tatler correctly points out that although there is no need to *maintain* highly detailed information (since the world can be used as an external memory; Stroud, 1955; Dennett, 1991), there is nevertheless a need to *use* (and therefore represent) it. The only real contention here might be his assertion that this level of representation is precategorical, because of the precision involved. However, the formation of proto-objects (either individually or in groups) is highly sensitive to spatial position (Rensink and Enns, 1995), and it may be that the sensitivity to spatial position is simply a consequence of this.

Regarding the kind of information that might be preserved in the setting system, Tatler provides a nice assay of the time course of the development of different possible kinds of information. Results show an early (and almost immediate) development of gist information, followed by a progressive buildup of layout information. This is consistent with the operation of the triadic architecture proposed by Rensink (2000c); indeed, the results argue for layout being constructed by the sequential entry of fixated items into a more durable representation that does not require attention for its maintenance. It is an open issue as to how much information can be accumulated this way. However, if the representation of layout is to remain reasonably abstract, only a minimal amount of information can be maintained about each item. It is also important to keep in mind that nonattentional representations are not concerned with spatiotemporal coherence. Thus, even if a considerable amount of abstract information could be accumulated (e.g., Melcher, 2001), it would not be able to assist with the perception of *dynamic change*, although it might facilitate the detection of *difference* (Rensink, 2002b).

Preservation of attended information

The question of how much attended information is preserved across saccades is explored in an elegant way by Deubel et al. (2002), who examine how information from the presaccadic display interacts with information in the postsaccadic display. Their studies are based on the *blanking effect* (Deubel and Schneider, 1996), where the blindness to displacements made during saccades can be 'cured' by briefly blanking the saccade target after the eye has arrived at its new position. This effect suggests that more information may survive across saccades than would expected from change-blindness work. Deubel et al. carry out several interesting experiments that investigate this possibility.

The initial set of experiments investigates the preservation of position information. Deubel et al. present a nice summary of previous work showing that this kind of information is unlikely to be maintained across a saccade with a high degree of accuracy. They then propose that the position of any item in the vicinity of the estimated position will be taken as the reference location. Their experiments show evidence that an estimate of the postsaccadic position of the saccade target is also carried across the saccade, but that this is used only if no reference item is present.

This view of the transsaccadic preservation and integration of information is consistent with the framework described earlier, since given that a saccade target is an attended item, a certain amount of information about it will be held in stable form (including position information). The main addition here is a mechanism to cope with expected changes due to the saccade itself, namely, an anticipatory formation of a new link from the nexus to the estimated postsaccadic location.

An interesting issue that emerges from this proposal is the status of the blanked item. Deubel et al. argue that if the reference item is not found in the postsaccadic display, the assumption of stationarity is given up, and it is assumed that the item has moved elsewhere. However, it may also be that the blanked item is simply considered to be occluded (with its anticipated position left unchanged), and that its unblanking is interpreted as a shift to a new position where it is no longer occluded.

Deubel et al. also show that a similar kind of blanking causes a similar kind of increase in the ability to detect changes in other properties, such as shape. Owing to issues of projection, receptor density, etc., the representation of a given shape depends on its location on the retina, and it is certainly possible that a similar kind of anticipatory mechanism is used.

However, the experiments used to investigate this issue involved only a brief display of the presaccadic item, and so there may simply have been insufficient time for its consolidation in (attended) visual short-term memory. In other words, without the blank the consolidated representation might have been a combination of pre- and postsaccadic views, making detection of change unreliable. The insertion of the blank may have served simply to allow time to consolidate the (attended) presaccadic representation, or at least to mark it off as a distinct object. One test for this would be to repeat these experiments with a longer exposure of the stimulus (say, 300 ms) before the saccade is initiated. If blanking effects were still found, this would support the anticipation hypothesis; if not, it would support the consolidation hypothesis.

Access to detailed information

De Graef and Verfaillie (2002) provide a direct examination of the extent to which detailed information (i.e., the information in the array of detailed, volatile proto-objects) can be carried across a saccade and then accessed by various visual processes. Transsaccadic memory has often been presented as a limited-capacity system (often identified with visual short-term memory and attention); however, various studies indicate that other kinds of information are also preserved across saccades (see e.g., Tatler, 2002). De Graef and Verfaillie examine the possibility that the array of detailed information (in what they term a *visual analog*) can survive a saccade, and can be entered into subsequent descriptions of (coherent) objects.

The approach taken by De Graef and Verfaillie is an interesting variant of the technique used by Becker et al. (2000), namely, detecting change in a postsaccadic item that has been cued during the saccade. As in the case of Deubel et al. (2002), they find that a brief blanking creates some ability to detect change in the three-dimensional orientation of a saccade target, and that any blank of 50 ms or more is sufficient for this. However, if the item cued is a bystander object (i.e., not a saccade target), the observer remains unable to detect changes in its orientation. They argue from this that there is some ability to extract information from a visual analog, but that there remain some mysteries as to the details of its operation.

As De Graef and Verfaillie point out, the notion of a visual analog is similar to the idea of informational persistence (Irwin and Yeomans, 1986), and this in turn can be related to the memory trace of the array of proto-objects in early vision (Rensink, 2000b). All these descriptions concur in positing a dense array of items. Indeed, the proposal by De Graef and Verfaillie that the visual analog can represent in-depth (or three-dimensional) orientation is echoed in the findings of Enns and Rensink (1991) that early-level processes can form proto-objects that describe three-dimensional orientation.

There is less agreement, however, on the issue of whether proto-objects are moved during a saccade (resulting in a spatiotopic array) or whether they remain stationary (resulting in a retinotopic array). The work of Duhamel et al. (1992), for example, shows that receptive fields begin to anticipate saccade shifts, at least for fixation targets, and presumably all other attended items as well. However, it is an interesting question whether a similar translation takes place for the nonattended items.

The experiments of De Graef and Verfaillie are a good first step in addressing this question. However, their current design leaves open the possibility that no access to the proto-object array (or visual analog) is involved. To begin with, in the case where the cued item is the saccade target, the pattern is much the same as that found by Deubel et al. (2002), and an explanation of this can be given entirely in terms of the stabilization of the (attended) saccade target. (The lack of decay is exactly what would be expected of an attended item held in short-term memory.) Meanwhile, the failure to detect change in cued bystanders could be explained simply by a failure to access detailed information. Note that this failure does not imply that the volatile, detailed description has been completed destroyed by the saccade; rather, it may simply be that by the time attention has reached these items, they have simply decayed too much. (Indeed, the hint of improvement for the 50 ms blank may be due to the vestiges of this representation.) But as De Graef and Verfaillie suggest, a resolution of this issue can be obtained by further experiments that examine the effect of initial exposure, blank time, and cue time on performance.

Summary

As the chapters in this section show, change perception provides a powerful way to explore various aspects of vision, including implicit perception, the nature of visual attention, and the degree to which information is accumulated across saccades. Moreover, these results can be consolidated into a picture that casts light on the general architecture of the visual system. The picture that is emerging is one of a highly dynamic, 'just in time' system, in which the conscious perception of coherent structure is just one of several aspects of visual perception.

Thus, the study of change perception is changing many of our ideas about visual perception, as well as our ideas about change itself. Given that all things change, it is unlikely that we will ever arrive at a final picture of these matters. Nevertheless, it appears likely that we will continue to increase our understanding of how vision works, and it appears likely that much of this will be achieved by studying the perception of change.

Acknowledgements

The author would like to thank NSERC (Canada) for its support during the preparation of the manuscript.

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