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# 24

# Representational Buffers: The Eye–Mind Hypothesis in Picture Perception, Reading, and Visual Search[1]

## I. Buffers in Visual Processing and Eye Movement Control

A buffer, as the term is used here, is a memory device that maintains information at a particular stage of processing. During the time the information is maintained, it is available to later stages of processing. A familiar example is iconic memory, which is thought to maintain a sensory-like visual representation for a short period during which a later process such as identification can operate. The term "buffer" focuses on the transient nature of a given memory representation and the flexibility it gives to the timing of the next stage(s) of processing.

In the case of the control of eye movements in reading and the perception of scenes, there may be several levels of buffering. The significance of the buffers is that they permit some degree of decoupling of the eye and mind. The methodological implication is that buffers reduce the sensitivity of eye movements as immediate indicators of mental processing.

The relevant buffers for which there is at least some evidence include the following eight. It should be emphasized that the characterization of these buffers is tentative. I present some of the evidence for each buffer and discuss its functional significance for eye movements.

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*EYE MOVEMENTS IN READING*
*PERCEPTUAL AND LANGUAGE PROCESSES*

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*Input buffers* (vision)

1. Retinotopic icon or "visible persistence," localized in relation to the retinae.
2. Spatiotopic visual memory, localized in the visual world.
3. Reatopic visual memory, representing spatial relationships internal to some visual object or pattern ("res" is the Latin word for "thing," as in "real").

*Central buffers*

4. Acoustic/phonological/articulatory short-term memory (STM).
5. Conceptual very-short-term memory.
6. Working memory.

*Output buffers* (for eye movements)

7. Location of next saccade.
8. Timing of next saccade.

A visual event does not necessarily enter the buffers in the order given here. It is assumed that certain pairs of buffers are linked by processes that transform information from one to the other buffer. The relative timing and direction of flow of information is constrained by these links, which operate automatically or under central control. A diagram of possible connections among the buffers is given in Fig. 24.1 (Section III).

## A. Buffer 1: Retinotopic Icon or "Visible Persistence"

Iconic memory has been extensively studied since Sperling revived the phenomenon in 1960. Most researchers have assumed that the subjective impression of continuing vision after the stimulus has stopped is what permits selective processing of some part of the array, in Sperling's partial-report paradigm. Recently, however, Coltheart (1980) has argued persuasively that visible persistence of the sort mediated by the photoreceptors (e.g., Sakitt, 1976) and probably also by some later stages in vision is *not* the basis for the poststimulus cuing effect in the partial-report paradigm, which is instead due to some later (more central) stage of processing (Buffer 3 or 5, in the present scheme).

It is worth looking briefly at Coltheart's argument, for it is a model of how one can dissociate buffers. His approach is to determine whether variables that affect persistence of vision also affect partial versus whole report in the Sperling task. He discusses seven different experimental procedures that seem on their face to measure *visible* persistence. Each of these compares some behavioral measure with the physical duration of the stimulus. The seven are: (*a*) judgment of synchrony between the visible offset of a target stimulus and the onset of a visual or auditory probe stimulus; (*b*) response latency to the onset and (apparent) offset of a stimulus; (*c*) stroboscopic illumination of a moving stimulus such as a single spoke; persistence is measured by the number of spokes reported to be seen simultaneously; (*d*) the moving-slit technique in which a stimulus is "painted" over the

retina; (*e*) phenomenal continuity of an intermittent stimulus; (*f*) temporal integration of two incomplete figures; and (*g*) stereoscopic persistence, which can be distinguished from the persistence of the monocular input to the stereoscopic system and which is therefore cortical in locus. In most of these paradigms, visible persistence lasts from 0 to 150 msec; in the case of stereopsis, 300 msec.

Coltheart noted that all these measures of visible persistence indicate that within certain ranges, visible persistence is *inversely* related to luminance and to stimulus duration. In contrast, partial-report superiority is *unrelated* to luminance and stimulus duration, over the same range, provided that they are "adequate for legibility." Therefore, concludes Coltheart, visible persistence is not the basis for Sperling's iconic memory, which is measured by the persistence of information that is not necessarily in the form of a visible array (see Buffers 2–5). (Coltheart's conclusions have been questioned or qualified by Bowling & Lovegrove, 1982, and Long & Beaton, 1982.)

Coltheart also reviewed the possible neural basis of visible persistence and concluded there were several loci (in effect, several buffers of Type 1): Candidates are the photoreceptors (Sakitt, 1976) and the sustained cells of the ganglion cells, lateral geniculate nucleus, and the visual cortex. Stereoscopic effects also indicate central visual persistence.

From the point of view of eye movements, what is the significance of Buffer 1, visible persistence? I would argue that in normal perception it plays no role except perhaps to sustain vision during blinks and possibly during saccades, until the next fixation. (But even in these cases some later buffer is as likely to be the functional one.) Of course, the phenomenon of persistence reveals characteristics of the visual system that are functionally important, but their function is not to outlast the stimulus—that consequence is incidental, and becomes functional only in the laboratory tasks listed earlier. (Haber has commented that visible persistence would only be useful for reading in a lightning storm.) Thus, Buffer 1 is a possible source of artifacts or mistaken interpretations in experiments that study eye movements using interrupted stimuli. Otherwise, it has little significance as a buffer. Note that persistence is usually eliminated by a following stimulus, provided that the two stimuli are sufficiently different and have a stimulus onset asynchrony (SOA) of about 30 msec or more; otherwise there is integration, as in (*f*) above. Persistence would thus ordinarily be terminated by the next fixation.

## B. Buffer 2: Spatiotopic Visual Memory

In perception, the retinally organized information from successive fixations is put together to produce the impression of a continuous, stable visual world. Several investigators have shown that this spatiotopic representation persists at least briefly after the stimulus has been removed (though for how long has yet to be investigated), that the representation can survive masking (at least if the subject attends to it), and that under some conditions the representation permits the visual integration of successive fixations. (For a related distinction between two visual buffers, see Mewhort, Campbell, Marchetti, & Campbell, 1981.)

Jonides, Irwin, and Yantis (1982) found that two stimuli presented in successive fixations can be seen as one figure, provided that they appear in the same location in visual space (and hence in *different* retinal locations). Davidson, Fox, and Dick (1973) showed something similar. A subject viewed a letter string on fixation N, replaced on fixation N + 1 by a ring around the place where one of the letters had been. The subjective appearance was of a ring surrounding the letter that had been at that location in visual space, whereas the ring masked (blanked) the letter that had been at the ring's *retinal* location. That is, subjects "saw" an array of letters in which one letter was missing and another letter was visible but surrounding by a ring. Metacontrast masking was retinotopic (Buffer 1), whereas perceived overlap was spatiotopic (Buffer 2). (It should be noted that some laboratories have been unable to obtain the spatiotopic overlap reported by Jonides *et al.* and by Davidson *et al.*; cf. Breitmeyer, Chapter 1 of this volume.)

Hallett and Lightstone (1976a, 1976b) obtained evidence for spatiotopically controlled eye movements in an important set of experiments. The task was simply to track a light spot in an otherwise dark environment. When the eyes were in mid-saccade to one target position, the target was moved to a second position and then extinguished. Thus, the only information about the second location was obtained while the eyes were moving. In the dark that followed, the eyes were immediately and accurately directed to the second position in space. This shows that the oculomotor system had accurate information about the momentary position of the eyes relative to the stationary head, during the saccade, and could combine that information with information about the retinal position of the target to determine where to move the eyes next. (Incidentally, the experiments also show that saccadic suppression is not absolute.) Experiments on monkeys in which the superior colliculus was stimulated to produce an inappropriate eye movement after the target had been removed (Mays & Sparks, 1980) gave a similar outcome.

Whether it is appropriate to think of such eye movement control mechanisms as making use of a "representation" of space is unclear. The neural computation may result in appropriate targeting of the eyes without (for example) providing the kind of general purpose map that could be used for reaching, or for reporting location. Reported location is often erroneous under the conditions of the Hallett and Lightstone experiments. Thus, it seems likely that the oculomotor system's spatiotopic performance is not invariably based on the representation I am calling Buffer 2.

### 1. SIGNIFICANCE OF BUFFER 2 FOR PERCEPTION WITH EYE MOVEMENTS

The purpose of some representation like that of Buffer 2 is to integrate successive views, taking into account head and eye movements. There have been no studies to my knowledge that examine the duration of this form of memory, so it is difficult to assess its importance as a buffer. One test of the duration of this type of representation would be to discover whether information can be integrated over three fixations. An additional question is what processes other than pattern recognition (e.g., Jonides *et al.*, 1982) and localization are based on the output of Buffer 2. One possibility is that the location of the next fixation (Buffer 7) is ordinarily determined at this level, in reading, based on the position of spaces and the lengths of words.

## C. Buffer 3: Reatopic Visual Memory

Another form of short-term visual memory (STVM) in which the spatial or retinal location of successive views is less important than their overall similarity as patterns has been identified by some investigators. Phillips (1974), for example, showed subjects a matrix of 16 to 64 cells, half of them filled, and then a second matrix with no or one cell changed. He found evidence for a high capacity parallel store lasting about 100 msec (Buffer 1, presumably) and a second store that remained intact for some 600 msec and then decayed only slowly (if the subject was not distracted) over a period of 9 sec. This STVM for the pattern was distinguished from the brief sensory memory in that it exhibited limited capacity (larger matrices being less accurately remembered), was less sensitive to backward masking than the sensory store, and was tied neither to retinal nor to environmental location.

To demonstrate the latter, Phillips displaced the second matrix with respect to the first. That interfered markedly with sensory memory (i.e., when the interstimulus interval—ISI—was short) but minimally with STVM, as ISIs of 300 and 600 msec (the longest ISIs used). There was no control over eye movements during the ISI, so it is likely that subjects had made an eye movement during the longer intervals, the same intervals in which displacement of the stimulus had no negative effect. This indifference to precise spatial position contrasts with Buffer 2, where consistent alignment in space is evidently important. That indicates that Buffer 3 does not take input exclusively from Buffer 2, but also (or instead) takes it directly from Buffer 1. (Bear in mind that Buffer 1 is probably heterogeneous and includes cortical as well as peripheral stages.)

In research on eye movements during reading, O'Regan (1981) tried shifting the text three character-spaces to the left or right during a saccade. This turned out to be imperceptible to the reader (although it did lead to changes in subsequent eye movements that can be explained by the nonoptimal location of the shifted fixation). Insofar as the appearance of the text on two successive fixations was being integrated, the integration was based on a local form rather than on precise localization in visual space.

A major question is whether Buffers 2 and 3 are indeed independent representations that are space centered and object centered, respectively, or whether there is just one localization system. One possibility is that there is a single system that can be driven either by information from the eye–head system or by pattern information, whichever happens to dominate the system. If so, it should *not* be possible to integrate two successive views (or fixations) and at the same time to know whether the second had been displaced with respect to the first. There is at least one case when we can do both: apparent movement. Therefore, we can reject the either–or model.

The case of apparent (or real) movement is instructive, because it shows that the world centered and object centered representations must not only coexist but also interact, to produce the effect of a stable world with some moving objects (e.g., Rock & Ebenholtz, 1962). The phenomenon of induced movement (as for example when the moon appears to move behind clouds) demonstrates this interaction particularly vividly.

Another case in which retinal, spatial, and object-centered information seem to be independent has been discussed by Burr (1980). He asked the question why moving objects in the environment do not ordinarily look blurred or smeared across the scene. Since it is known that visual signals are summated over about 100 msec, objects in motion while the eyes were fixated might be expected to look blurred (as in a 1/10 sec photographic exposure). However, Burr found that as long as the objects moved for a long enough time to produce a sensation of motion (about 75 msec) there was virtually no smear: A clear object was seen as moving.

Since spatiotopic and reatopic representations are obliged to interact in interpreting movement, are the two representations part of a single buffer that represents both the stable world frame and pattern shifts (moving objects) within the stable world? That seems unlikely. The system that compares two temporally separated patterns and concludes that they are the same continuous object is logically separate from the system that corrects for head and eye movements to produce a visual world fixed in relation to the observer. A thorough discussion of these issues would take me too far afield; for examples of recent pertinent work, see Berbaum, Lenel, and Rosenbaum (1981) and Ullman (1979). Another reason for considering the reatopic representation to be distinct from the spatiotopic one is that in Phillips' experiments there was no apparent movement at the longer ISIs, just "knowledge" that the second pattern did or did not differ from the first.

There are three findings that raise the question of whether Buffer 3, which is object based, is visually "literal" or is somewhat more abstract. In apparent movement there is considerable tolerance for pattern changes, particularly if the second form is a possible rotation of the first form (Berbaum *et al.*, 1981), and indeed Ullman demonstrates that such movement transformations can reveal three dimensional shape. Here, the abstraction is from a two to a three dimensional object. Another level of abstraction is to a conceptual equivalent, for example, *a* and *A*, or *r* and *R*. Two studies suggest that such an abstraction may take place at an early stage in perception. One is the observation (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980) that readers neither notice nor are affected by a shift from (say) *aPpLe* to *ApPlE*, in successive fixations. The second is Friedman's finding (1980) that under near threshold conditions a reader reports the identity of letters such as *a* and *A* more accurately than their case (upper or lower). In both investigations the effect was immediate, not the consequence of forgetting in the ordinary sense.

The possibility that reatopic organization can be based on identification of an equivalence class of objects, not just on two dimensional shape as given on the retina, raises the question of its relation to later buffers that are clearly postidentification. An important related question is whether information from one or more other senses is combined with visual information at this level, as in the synchronization of a speaker's voice and face.

### 1. BUFFER 3 AND EYE MOVEMENT CONTROL

The ability to retain information about a visual pattern for as much as several seconds (Phillips's STVM) despite visual masking suggests that it would be possible for the eyes to keep on reading or viewing a scene while the later perceptual system remained focused on an earlier glimpse. Note, however, that Phillips showed that viewers lost the contents of STVM if they attended to a subsequent visual stimulus or carried out mental arithmetic. Thus, in normal circumstances there is no reason to expect this buffer to decouple the mind and eye, for the eye is functionally blind as long as the buffer's old contents remain the focus of attention. Only in unusual circumstances (such as catching a fleeting glimpse of something of great importance) would this buffer be used to dissociate the focus of perceptual attention from the current focus of the eyes. Ordinarily, as the bulk of eye movement research shows, the eyes linger where the attention is focused.

## D. Buffer 4: Acoustic/Phonological/Articulatory Short-Term Memory (STM)

I have characterized Buffers 4, 5, and 6 as central because they clearly entail learned recoding of visual stimuli. Since the same may be true of Buffer 3, the distinction between input and central buffers is somewhat arbitrary. If we were discussing auditory stimuli, Buffer 4 might be regarded as an input buffer roughly equivalent to Buffer 3 for vision.

The equivocation about the nature of the representation in Buffer 4—acoustic, phonological, or articulatory—respects a continuing theoretical dispute that I will not elaborate on here (cf. Baddeley & Lewis, 1981; Crowder, 1976, for reviews). The buffer is chiefly relevant for verbal material or the names of nonverbal material.

### 1. READING AND THE PHONOLOGICAL BUFFER

The use of this buffer in reading, once regarded as the resort of beginning and slow readers, has undergone a rehabilitation in recent years and is now regarded by some theorists as important in skilled adult reading (e.g., Baddeley & Lewis, 1981; Schankweiler, Liberman, Mark, Fowler, & Fischer, 1979). Petrick and Potter (in preparation) showed that recoding into an "acoustic" form occurs even during very rapid reading: How far recoding lags behind the eye is not known, however. It seems quite possible that recoding is accomplished during the fixation on a given word; in fact, Just has reported (personal communication, Dec. 11,

1981) that gaze duration on a word in silent reading is strongly correlated with speaking time. The details of the way in which the acoustic representation is used in reading have not yet been worked out, but its potential role as a relatively durable buffer capable of retaining at least the last clause is clear.

## E. Buffer 5: Conceptual Very-Short-Term Memory

Immediately after one has understood something—a word, picture, or whatever—there seems to be a very short interval during which the thought can be interrupted irretrievably by a second cognitive event, if that event commands attention. The relationship between the two events as well as their timing determines whether Event 2 masks Event 1 or enhances it. Because the interval of high susceptibility to cognitive masking is very brief (e.g., 1 sec or less), it is difficult to demonstrate unequivocally that there *was* transient understanding. That may be the reason that little attention has been paid to this buffer in comparison with the acoustic buffer (conventional short-term memory).

Evidence for the existence and the conceptual nature of very-short-term memory comes from work with meaningful pictures. Complex scenes presented rapidly in a sequence are unlikely to be remembered verbally, so Buffer 4 (acoustic STM) is not confounded with putative Buffer 5. The claim that one can momentarily understand but immediately forget such scenes (Potter, 1975, 1976; Potter & Levy, 1969) was made on the basis of the following argument and experimental results.

1. Detection of a semantically specified target picture (such as "a boat"), presented in a rapid sequence of diverse pictures, would only be possible if that picture were processed to a conceptual level, because the range of photographs meeting that semantic description is too broad to permit advance "physical" specification of the target.
2. If the target pictures are chosen randomly, then the detection rate is an index of the proportion of pictures in the sequence that were momentarily identified to a level that permitted matching to the semantic description. (This estimate is conservative, because the target-matching task might require cognitive resources that would otherwise be devoted to picture comprehension.)
3. In experiments of the kind described, semantic targets can be picked out more than 60% of the time when pictures are presented for 113 msec each, in a continuous sequence, and almost 90% of the time at 250 msec per picture (Potter, 1975, 1976).
4. If there is no very-short-term conceptual memory, then forgetting of "understood" pictures should follow the normal course of short-term forgetting of pictures, which many investigators have shown to be a slow decline—that is, pictures are ordinarily remembered remarkably well for days or weeks after viewing (Nickerson, 1965; Shepard, 1967; Standing, 1973). One would therefore expect that subjects who simply viewed the sequence of pictures would remember almost all of the pictures they had understood, if they were given a recognition test right after viewing the sequence. Thus, if subjects in the detection task could detect 60% of the pictures at a given rate, subjects in the recognition memory task should recognize about the same proportion.
5. In a recognition memory experiment with the same sequences used in the detection experiment, subjects performed much more poorly than in the detection task: At 113 msec, they recognized only 11% of the pictures (compared with over 60% detected), and at 250 msec, only about 30% (compared with almost 90%). The pictures were easy to remember, however, if shown for 1 sec each, when over 80% were recognized, or 2 sec, when over 90% were recognized (Potter & Levy, 1969).
6. Results (3) and (5) are incompatible with the assumption that simply understanding a picture is enough to stabilize its memory, even for a short time. The disparity between understanding (which takes only about 100 msec for the average picture) and normal short-term retention (which takes 1 or 2 sec of processing to establish) implies that there is an intervening very-short-term conceptual memory that is readily disrupted by the following picture in a sequence.
7. This memory is not disrupted by a pattern mask. Since we know by (3) above that the picture was understood during viewing or very shortly thereafter, it is appropriate to call this transient postmask memory *conceptual* rather than *visual*.

In a series of recent studies, Intraub (e.g., 1980) has replicated and extended Potter's findings. She has shown that even a negative target ("not an animal") can be detected more readily than the same picture can be remembered immediately after viewing (1981). She has also shown that a following picture is only (or chiefly) disruptive *if the viewer attends to it*. This strengthens the evidence that the very-short-term memory involved is indeed conceptual and is to a large extent under the viewer's control.

### 1. IS BUFFER 5 SPECIALIZED FOR MOMENTARY COMPREHENSION OF SCENES?

I speculated (Potter, 1976) on the basis of the evidence reviewed here that a viewer can understand each fixation, at the usual rates of eye movements, even if the fixation contains entirely unexpected information. (That, after all, is the most important kind of information.) This understanding allows appropriate control of subsequent fixations. It is not necessary, however, to retain the information in every fixation, so what chiefly gets remembered is a conceptual abstraction from the information in a series of fixations (e.g., Guenther, 1980). A recent experiment demonstrated that pictures in a short rapid sequence *can* be integrated, when they form a meaningful "story" (Inui & Miyamoto, 1981).

The same kind of short term conceptual information might be important in other cognitive tasks such as reading. Forster (1975) argued that readers could momentarily understand words seen for only 63 msec in rapid sequential visual presentation (RSVP), although they could only retain about half of a seven-word sentence presented at that rate. Although the minimal time per word may not be as low as Forster claimed, other RSVP research supports Forster's claim for a marked disparity between understanding and retention, similar to that for pictures.

### 2. RELATION TO BUFFERS 1–4

Clearly Buffer 5 is not localized either retinally (Buffer 1) or spatially (Buffer 2), but its relation to Buffer 3 (reatopic short-term visual memory) is less clear. Simply on the basis of the logical distinction between visuospatial characteristics of a viewer-centered scene (a scene seen from a particular vantage point) and the conceptual significance of the scene (or an RSVP sentence), one might expect such a distinction to appear in processing. On the other hand, it could also be argued that the two kinds of information are represented in a single format (e.g., in propositions). The issue cannot be settled until it can be shown that the two putative buffers have different retention characteristics or respond differently to variables in a way that would not be expected if the propositional account is correct. (See Avons & Phillips, 1980, and Walker & Marshall, 1982, for some evidence of this kind.)

As for Buffers 4 (acoustic) and 5 (conceptual), there are obvious differences, both in what sort of information is represented and in time course. A scene's meaning can be represented in Buffer 5 without any corresponding representation in Buffer 4. Buffer 4 seems to remain available for at least 2 sec without attention, whereas Buffer 5 is transient, serving merely as a bridge into longer term memory.

### 3. BUFFER 5 AND EYE MOVEMENTS IN READING

Buffer 5, the first and perhaps the only "thinking" buffer, is at a level at which thoughts are separated from words. Since the conceptions expressed by sentences are represented by mental entities that do not stand in a perfect one-to-one relation to words, there is necessarily a level at which the serial intake of a sequence of words becomes partially dissociated from the conceptual structure being built. One might expect the eyes sometimes to lead and sometimes to lag behind the developing structure of thought, with the words accumulating in one of the earlier buffers in the former case, or skipped over briefly in the latter case (e.g., Ehrlich & Rayner, 1981).

If conceptual short-term "memory" is identified with active thought, then one can estimate the span of thought to be less than a second: That is, to influence each other, elements of thought must have been activated within that span. A possible evolutionary reason for the fragility of ideas in the first few hundred msec is to avoid cluttering longer term memories (such as working memory, next section) with all the momentary conjunctions of thought that "go nowhere." Only the more successful ideas (like the correct identity of a word or object, or an appropriate development of an embryonic thought, or the solution to any microproblem then active) last long enough to be stabilized in working memory.

The idea that thoughts may form and dissolve within a second may seem farfetched. Consider, however, the ability to read and understand an RSVP sentence presented at 12 words a second (to be discussed in Section VI). That is a rate of presentation at which only about three words from an unrelated list can be reported (unpublished experiments in my laboratory). The difference between unrelated words and sentences, at this rate, implies that conceptual operations occur very rapidly and determine what enters the more stable buffers, Buffers 4 and 6.

## F. Buffer 6: Working Memory

If Buffer 5 is the active conceptual processor, how is it distinguished from working memory? (Note that the term "working memory" is sometimes used to encompass all forms of short-term memory, *e.g.*, Buffers 3, 4, 5, and 6.) My basis for the distinction between Buffers 5 and 6 is the time course, which is very brief for Buffer 5 and longer (perhaps up to 10 sec) for Buffer 6. Our principal recent thoughts remain accessible for a time in working memory, available to be retrieved rapidly and reentered into Buffer 5 state. No cognitive work is carried out in working memory, however. This memory is clearly conceptual, not visual or acoustic. It seems probable that many of the classic studies of short-term memory and memory retrieval reflected a mixture of acoustic, visual, and conceptual representations, however.

## G. Buffer 7: Location of the Next Saccade

Pollatsek and Rayner (1982) provide evidence that, in reading, the location of the next saccade is decided on the basis of the first 50 msec of the current fixation. This does not mean that, in real time, the decision is made by 50 msec, for by that time visual information has barely reached the striate cortex. Instead, it means that the next location is committed by the time the first 50 msec has been processed centrally (that *could* be as early as Buffer 2, the spatiotopic representation). Assuming that the movement is not initiated as soon as the location has been selected, there must be a buffer that holds the information until a triggering event occurs.

## H. Buffer 8: Timing of the Next Saccade

Although under most conditions the timing of the next saccade is under at least partial control of information processed from the current fixation, there are some circumstances (such as those indicated by Vaughan, Chapter 23 in this volume) in which saccade timing is partially or entirely preprogrammed. Such preprogramming amounts to a timing buffer.

## III. Questions about Buffers

### A. How Many Buffers?

As already indicated, it is not clear that all these buffers (forms of memory, levels of representation, processing stages) are distinct. Before rejecting this proliferation of buffers, however, one should note that physiology and anatomy suggest a much larger number of distinct levels, stages, or channels of processing. Which (if any) of these physiological stages serve as buffers in the present sense remains to be shown (only in the case of Buffer 1 are there any clear ideas). In any case, it must be emphasized again that the present list is only provisional.

One other buffer, long-term memory, has been omitted from the list because the focus is on buffers at the scale of eye movements. In principle, however, long-term memory serves the same functions as the other buffers, albeit on a much more extended scale: It holds information until called on by other processes. Long-term memories are probably associated with several of the buffers, not just Buffers 5 and 6 (the conceptual buffers). For example, object or word identification would require information of the kind represented in Buffers 1 and 3; memories of spatial layout, Buffer 2; and recognition of spoken words, Buffer 4. To what extent imagery (which draws on memory) employs one or another buffer is an active question (e.g., Baddeley & Lieberman, 1980).

The buffers are not arranged strictly in series. In the nature of such buffers, they operate in cascade, providing input continuously to the processors that link the buffers (McClelland, 1979). Moreover, the buffers are not strictly ordered. For example, information probably passes in parallel from visual to phonological and conceptual memory. Other examples have already been mentioned. The timing buffer (Buffer 8) may be filled either earlier or later than that for location (Buffer 7), according to Rayner and Pollatsek (1981); that is, Buffers 7 and 8 are independent. Some other buffers, however, are ordered more strictly: For example, Buffer 1 must precede all others, in vision.

### B. Variability of Processing and the Role of Buffers

A stage of processing with a single impulse as its output cannot act as a buffer; a buffer implies a continuing output of roughly the same information over some period of time. (Equivalently, the information is "available" for that period of time; I make no distinction between information "continuously flowing" and information available to be called by another stage.) The potential for buffering will only be realized in practice if the timing of the input to a given buffer is not perfectly correlated with the timing of the process that follows the buffer. Although I have dwelt on the many stages at which buffers may allow such dissociations, it is still the case that the eye and mind are ordinarily correlated, as other contributors to this book show. What the system of buffers permits is some flexibility in the timing of processing, in particular after the point of no return for the next saccade. If processing is not quite complete by the time the eye begins to move, one or more of the buffers can maintain the information until processing has finished, without necessarily requiring a regressive eye movement.

## III. The Buffers and Real Time Processing

Several attempts to estimate the time course of processing from the onset of a given fixation to the next saccade and fixation have been made (e.g., Becker & Jurgens, 1979; Carpenter, 1981; Russo, 1978; see also McConkie, Chapter 5 and Breitmeyer, Chapter 1 in this volume). Figure 24.1 gives an indication of the time course of the present buffers, in reading with fixations of 220 msec and saccades of 30 msec.

It takes approximately 60 msec for information to reach the cortex, and 40 msec elapse from initiation of a central motor command to initiation of the saccade. Thus, Buffers 2–8 have a maximum of 120 msec (i.e., the fixation duration minus 100) to process information from the *current* fixation before the next eye movement is irrevocably committed.

There are various pieces of evidence concerning the distribution of this 120-msec period over the intermediate buffers. Rayner and Pollatsek (1981) have evidence that the *location* of the next fixation is chosen after only the first 50 msec of the current fixation has been processed. The earliest buffer that *could* mediate the choice of location is Buffer 2 (spatiotopic). Adding 60 msec of Buffer 1 plus 50 msec of Buffer 2, the location (Buffer 7) is chosen 110 msec after the fixation, and delivers its message to the motor command system no later than 180 msec. Thus, the intended location is held in the buffer for 70 msec, when the total fixation duration is 220 msec. It is not clear whether location could be altered during that hypothetical wait, if the spacing of words to the right *changed* rather than disappeared after 50 msec. Since saccade timing is controlled independently of location, cancellation or delay of the saccade would presumably allow resetting of the intended location.

I have assumed that Buffers 2 and 3 take input directly from Buffer 1, at the same time, since I know of no evidence that specifies whether the spatial framework (Buffer 2) is computed before or after pattern identity is determined (Buffer 3). Insofar as the spatiotopic representation is based on motor commands to the head and eyes, that information could be available in advance of the current fixation, but insofar as the representation requires a retinal error signal, it depends on retinocortical information which is not available for about 60 msec (when it might also be available to Buffer 3). Since there is evidence (reviewed earlier) that Buffer 2 requires both sources of information, there is no basis for assuming a difference in onset of Buffers 2 and 3.

Buffer 8, the timing of the next saccade, is ordinarily bypassed in favor of

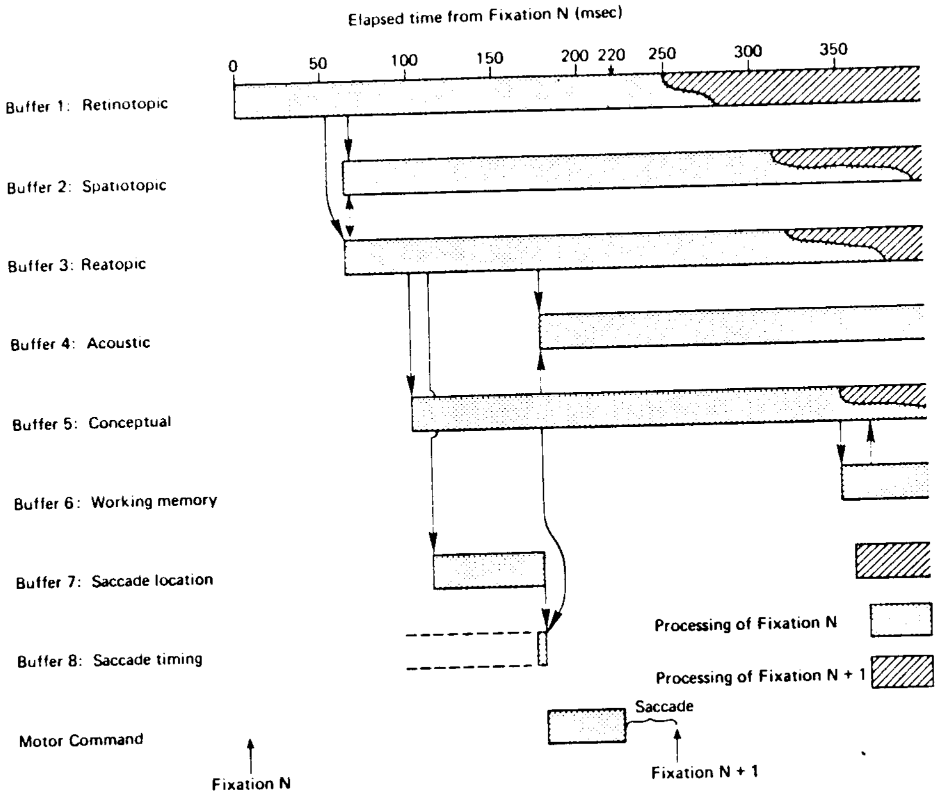

**FIGURE 24.1.** *A model of the temporal sequence of visual, cognitive, and response processes in eye movement control. Information from the following fixation,* N + 1, *is represented as merging with or replacing the information from fixation* N, *but arrows showing the flow of information are given only for* N.

"direct" central control of timing, presumably by Buffer 5, the thinking buffer in the present scheme. (In tasks simpler than reading, such as simple response to a light signal, the command might pass directly from Buffer 2 to the motor command system, bypassing Buffer 5 and the other central processors.) For control of timing that is based on the cognitive difficulty of the current word(s), Buffer 5 is required.

Various contributors to this book have presented evidence that the cognitive content of the last 140 msec of a fixation is incapable of influencing the duration of the fixation (that sounds as though it were a tautology, but the evidence is statistical). Using the same logic as before, 100 msec of that time would in any case be taken up with efferent (Buffer 1) and afferent (motor) processes, leaving by subtraction 40 msec for precognitive processing (processing that follows the 60 msec required to arrive at the cortex but precedes Buffer 5). Thus, we can estimate that it takes 40 msec to achieve an output from Buffers 2 and/or 3 to the conceptual level, Buffer 5: Buffer 5 thus begins processing the contents of the current fixation after a total of 100 msec. If Buffer 5 delivers the motor command directly (40 msec before the saccade begins), then there is about 80 msec of central (cognitive) processing before the next saccade is launched, in the case of a typical fixation of 220 msec. (In RSVP reading, 83 msec per word permits at least a shallow level of understanding; see Section VI.)

Buffer 6, working memory, takes input from Buffer 5 at the point that an item in conceptual short-term memory becomes stabilized, which can be estimated to be about 250 msec after arrival in Buffer 5 (i.e., 350 msec after stimulus presentation). This estimate comes both from the research with pictures described earlier and RSVP research referred to later. The time required for stabilization of material from Buffer 5 into working memory can be expected to be highly variable, however. It is appropriate to regard working memory as an inactive form of short-term conceptual memory that has no direct input into other processes, but whose contents may become further consolidated into long-term memory.

As for Buffer 4, acoustic short-term memory, a rough estimate of recoding time for visual words is 175 msec, based on a minimum word-naming latency of 400 msec and a simple articulation latency of about 225 msec, for a prepared response. Note that this would not allow any influence of exclusively acoustic–articulatory variables on the duration of the current fixation, only on the following fixation(s). One might be able to test this prediction by observing eye movements as a subject reads silently a sentence such as the following, with the instruction to look for sound similarities:

*The farmer explained that they use ewes rather than rams.*

### 1. THE IMMEDIACY HYPOTHESIS

Contrary to the strongest version of the immediacy hypothesis, it is likely that the criterion for initiation of an eye movement is set lower than the completion of all relevant cognitive processing of the stimulus. It seems most unlikely that the system would have built into it a substantial dead time (the 140 msec after commitment to the next saccade), and in any case we know that processing does continue, as witnessed by spillover effects on the duration of the next fixation and other evidence (e.g., K. Ehrlich, Chapter 5, Hogaboam, Chapter 18, and Wolverton & Zola, Chapter 3 in this volume; Danks & Kurcz, 1981). What *is* completed prior to initiation of the eye movement is a shallow level of understanding sufficient to diagnose orthographic, lexical, semantic, or syntactic difficulties.

At times, however, one might expect processing difficulties to become apparent only after the next saccade is committed, as just mentioned. Then, the buffers may be resorted to, to reprocess or continue processing information from the previous fixation(s); if the problem is not immediately solved, a regression would be programmed. This whole buffering effect should rarely create a desynchronization greater than the average duration of a fixation; otherwise, an appropriate regression or refixation would be expected.

## IV. Vaughan's Stimulus Delay Paradox: Can the Buffer System Explain It?

Vaughan's elegant experiments on eye movement latency in relatively simple tasks provide us with some puzzling facts:

1. When the subject looks to point X and then to the left or right depending on a signal at X, delay of the directional signal after the eye has arrived at X has little effect on oculomotor latency provided the delay is no longer than 60–100 msec. Further delay adds more or less linearly to the latency (Vaughan, 1978; Vaughan & Graefe, 1977; Vaughan, Chapter 23 in this volume). Rayner and Pollatsek (1981) have a related result in reading: Imposition of a mask for the first part of a fixation is undercompensated for when the mask lasts for 50–100 msec. Again, with longer lasting masks, there is virtually complete compensation. These observations are readily explained by a model of eye movement control in which there is preprogramming of fixation duration, with cancellation of the programmed movement when stimulus delay is long but not when it is short. As Vaughan shows in (2) and (3) following, however, this explanation must be rejected.

2. Vaughan adapted the Sternberg task in the following way. Subjects were given a variable memory set of letters and then they scanned alternately between two widely spaced letter locations, searching for any match between the visual letters and the memory set. Upon the eye's arrival at one of the locations, the onset of the test letter was delayed for a variable time, as in (1). Vaughan argued that preprogrammed durations should be insensitive to memory-set size, which is a factor affecting on-line processing. The preprocessing plus cancellation hypothesis would thus predict an interaction between stimulus delay and memory load, with little influence of memory load when delays were 100 msec or less and the preprogrammed saccade occurred.

But that is not what happened. Memory-set size added a constant time to oculomotor latency and did not interact with (1).

3. Furthermore, adding a mask to the test stimulus in the Sternberg task produced a small increase in oculomotor latency, but again did not interact with (1) as the partial preprogramming hypothesis would predict.

4. These facts become even more puzzling when an observation of Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1981) is added. Presenting the stimulus (text) for only the first 50 msec of a fixation, followed by a mask for the remainder of the fixation, causes virtually no change in oculomotor latency, the size of saccades, or reading accuracy. This result suggests that the first 50 msec of each fixation is all-important in reading, which is superficially at variance with (1) and with an experiment reported by Wolverton and Zola (Chapter 3 in this book).

To account for these results, the buffer model of Figure 24.1 might need to be modified. One possibility is that in a continuous task such as reading, conceptual processing (Buffer 5) sometimes runs behind perceptual uptake, so that perceptual information from the current fixation queues up briefly in one of the earlier buffers (2, 3, or even 4). As long as the delay of stimulus onset after fixation was no longer than the delay in entering Buffer 5 caused by the queue, the stimulus delay would have no effect on the duration of that fixation.

A different explanation of (1) was suggested by Rayner and Pollatsek. They proposed that the saccades in their experiment fell into two categories, those of normal latency as measured from the onset of the text (full compensation for the delay), and those initiated before any information from the text had been processed. The distribution of response time supported this hypothesis, not the queuing hypothesis.

Unfortunately, the superficially similar results reported by Vaughan and his colleagues cannot readily be explained in the same way. If the insensitivity to short delays was due to a subgroup of brief responses insensitive to the stimulus, then there would have been an interaction between delay and set size—see (2)—and between delay and visual degradation—see (3). There was not. Does the queuing hypothesis explain the Vaughan results? It is possible that there is a brief period of cognition preparation, after the eye arrives at the location of the upcoming stimulus, that delays the beginning of stimulus processing in Buffer 5. That would explain finding (1), albeit in a wholly ad hoc way.

The buffer model can readily explain finding (2). The larger the memory set, the longer the comparison process in Buffer 5. Finding (3), however, presents difficulties. Why should stimulus degradation have an effect on RT that is constant across delays? If the hypothesized queue occurs after initial visual processing, then the queue should absorb degradation at short stimulus delays. Possibly the degradation has an effect at the stimulus comparison stage, as has sometimes been reported in the Sternberg task.

Finally, according to (4), 50 msec at the beginning of a fixation (followed by a visual mask, for the balance of the fixation) is all that is needed to read perfectly normally. This result presents no difficulty; both Buffers 2 and 3 are posticonic, and 50 msec is presumably long enough to register written words in those buffers. (Note that the 60-msec cortical delivery time is irrelevant, because the mask also takes 60 msec to arrive; what matters is how long it takes for the retinal information to be fully encoded into Buffer 2 and/or 3, once it arrives there.)

### 1. THE WARNING SIGNAL HYPOTHESIS

Vaughan accounts for the insensitivity of a reader's eye movements to short stimulus delays, point (1) above, by proposing that the delay interval has the effect of a warning signal, compensating for the delay. In effect, he proposes that in the delay range 0–60 msec, there is a precise trade-off between the advantage of a warning signal and the disadvantage of a delay in onset of processing. The claim is strengthened by previous evidence that a warning signal does reduce oculomotor latency; the size of the reduction and its time course are comparable to the present delay effect.

Although this explanation seems quite satisfactory for simple eye movement tasks, it seems much less satisfactory when applied to stimulus delays in reading

(Rayner *et al.*, 1981) or in Vaughan's Sternberg task. Why does a reader or scanner *need* a warning that information will appear during the current fixation? For these more continuous tasks, the cognitive queuing hypothesis gives a more plausible account. It is even possible that the effect of a true warning signal (in Becker and Saslow's experiments, cited by Vaughan) is to "clear the cognitive decks"—that is, reduce the delay in entering Buffer 5. If so, one effect of a warning signal should be to interrupt cognitive processing of prior material—a testable prediction.

## V. Applying the Model to Picture Viewing

### A. A Comparison with Loftus's Views

It is worth considering how the model of Figure 24.1 would account for some of Loftus's observations about picture processing. The cascade notion and the processing-time control over the duration of a fixation are both consistent with his views. The model's claim that there is poststimulus, postmask processing of visual information is not consistent, however: Loftus believes that one difference between reading and picture processing is that there is little postmask processing of pictures. He bases this conclusion on his own recent experiments (Loftus, 1981), showing that repeated brief exposures of a picture result in a recognition–memory performance that is at best equal to (and usually less than) the same exposure time presented continuously. If there were significant postmask processing, he argues, dividing the total time into several glimpses, each with postmask processing, should increase total processing time and thus improve performance. Since performance was not improved, Loftus concludes that there was not postmask processing.

There is, however, strong evidence from other studies that postmask processing of pictures does occur when the masking stimulus does not need to be attended to (Intraub, 1980; Lutz & Scheirer, 1974; Potter, 1976). Why do Loftus's experiments fail to show evidence for it? Loftus (1981) in fact gives a possible explanation: When a person views the *same* picture on successive occasions, he or she may automatically repeat the same initial steps of processing. Thus, information does not accumulate significantly over successive "glimpses" in Loftus's experiment unless the viewer happens to look at a different part of the picture. If Loftus is right about this, then his results do not contradict previous evidence for postmask processing.

An experiment that would usefully clarify this question would apply the masking techniques of Rayner *et al.* (1981) to picture viewing. The question would be whether the imposition of a mask during the latter part of each fixation would change the duration of the fixation and the extent of the subsequent saccade (as Loftus's hypothesis about continuous uptake would predict), or whether (as in

reading) the mask would produce little interference as long as its onset was delayed for some minimal time after picture onset—say, 125 msec.

### B. Comparisons between Pictures and Sentences

Loftus remarks that the gist of a text takes much longer to pick up than the gist of a scene. The only direct comparisons between scenes and equivalent descriptions that he mentions (Dallett & Wilcox, 1968; Nelson, Metzler, & Reed, 1974) were both concerned with memory, not initial processing. The same may be said of a number of more recent experiments addressing the question of the form of representation in memory of pictures and sentences (Baggett, 1975; Guenther, 1980; Pezdek, 1977; Rosenberg & Simon, 1977).

To discover how rapidly one extracts the gist of a picture or sentence, one needs a task that is immediate or almost immediate. In an experiment (Potter & Elliot, in preparation) comparing picture and sentence understanding, we obtained some indirect information on the relative times to extract the gist of pictures and sentences. Subjects in one group read a sentence and in a second group viewed a scene. The sentence or scene was immediately followed by a probe item (in the form of a line drawing or written word). The probe had not appeared in the scene or sentence, but was relevant to its meaning ("gist") on half the trials; the task was to decide whether the probe was relevant. For example, after the sentence *The tent is beside the lake*, the word *canoe* was the positive probe and *shoe* was negative.

The 5 to 12 word sentences were shown for 2 sec and the scenes were shown for 500 msec. The latency to respond to the probe was 171 msec longer following a sentence; that suggests that it took 2 sec + 171 msec to process the sentence to the same level as a pictured scene presented for 500 msec. This estimate is crude, but it does suggest that a picture is understood about four times faster than a comparable sentence. Incidentally, there was no difference between line drawings and single-word probes, either for sentences or for pictures. This supports the conclusion from other studies that the meanings of pictures and verbal materials are represented in a single underlying code, such as the conceptual code of Buffer 5.

### C. Visual Buffers in Scene Perception

Is there perfect synchrony of the eye and mind in viewing a scene? If the model in Figure 24.1 holds for both reading and scene perception, then the input to higher level processing (Buffer 5, the mind) is from a visual buffer. If the buffer integrates successive fixations into a unified spatial representation of the visual world that is corrected for eye and head movements, then the mind would get information that is at least one step removed from the information in a given fixation. But the truth is likely to be more complicated than this, because we do have some awareness of the scene as given in a single fixation. Thus, all three visual buffers—one organized retinotopically, one that represents a unified visual world, and one that is organized by objects—may be able to be read directly by the mind.

## VI. RSVP and the Buffer Model

Rapid serial visual presentation (RSVP) is a method in which word lists or sentences are presented one at a time at the same location, so that the viewer can read without having to move the eyes. The method permits the experimenter to control the duration of "fixations" and also the span of each fixation. Thus, it is complementary to eye fixation research in which those are the dependent variables. In RSVP, the dependent variables are latency to comprehend a sentence, accuracy of recall, latency and accuracy of target detection, and the like.

I will review briefly some results from RSVP research, discussing the relation of these results to the buffer model and to normal reading. A more detailed treatment may be found in Potter (1983).

1. College students can read and understand single sentences of 8–14 words (we have not tried longer ones) with considerable accuracy when they are presented one word at a time at 12 words per second (wps), that is, 720 words per minute (wpm) (Petrick & Potter, in preparation; Potter, Kroll, & Harris, 1980; Potter, Kroll, Yachzel, & Cohen, in preparation). These students would normally read only 300 wpm, although when pressed they can read the sentences (in normal format) at about 540 wpm. Thus RSVP seems to permit faster than normal reading, at least for single sentences.

I noted earlier that the presaccadic central processing time for the current fixation, in reading, may be as little as 80 msec: At that point, the reader seems to know just enough to carry on with the next fixation. At a steady state of 83 msec per word (with the word reaching the conceptual system—Buffer 5—about 100 msec after stimulus onset), the RSVP reader would pick up about the same amount as the presaccadic central processor, but would entirely miss the processing that occurs in normal reading between saccadic initiation and the central arrival of the next stimulus, which we estimated to be about 170 msec. (This calculation somewhat underestimates the time available for RSVP processing, because in normal reading the eye picks up fractionally more than one word per fixation.)

2. The rate limiting factor in RSVP reading seems to be memory storage, not initial comprehension (Frauenfelder, Dommergues, Mehler, & Segui, 1979; Potter *et al.*, 1980). The same seems to be true in picture perception (Potter, 1976); that was taken as evidence for very-short-term conceptual memory (Buffer 5). These results are consistent with the importance of the processing that follows saccadic commitment, a claim that most of the authors of this book agree with.

3. There is phonological encoding (as well as semantic encoding) during RSVP reading at 12 wps that is as marked as at the more normal rate of 6 wps (Petrick & Potter, in preparation). This finding is compatible with the present model, which assumes that there is input into Buffer 4 from Buffer 5 within about 65 msec.

4. When overall rate is equated, RSVP and conventional reading produce a similar level of understanding and retention (Juola, Ward, & McNamara, 1982; Masson, 1981; Potter 1983; Potter *et al.*, 1980; Potter *et al.*, in preparation). On the one hand, this finding offers support for the growing consensus that words outside the fovea receive little advance processing in normal reading, perhaps only that needed for eye movement guidance. On the other hand, the result suggests that the precise time the eyes dwell on a given word is not important, provided that the time is minimally sufficient for word recognition and the overall time across the sentence or text is adequate (Ward & Juola, 1982).

### A. Rate and Memory Consolidation: The Conceptual Buffer

Several questions about eye movements arise from these observations. If it is *possible* to read at 12 wps, why do most people read only 4–5 wps? The possibility that "eye movements are a waste of time" (John Sender's phrase) can probably be rejected, for there is a marked reduction in what is remembered when people read RSVP paragraphs at faster than normal rates. If the rate limiting factor in reading is memory consolidation, however, the extra time must be required at a rather abstract conceptual level, not at the level of individual word recognition, since 83 msec (preceded and followed by a mask) is ample time for word recognition. But the abstract conceptual level does not map one-to-one onto individual words, which ought to weaken the correlation between gaze duration on an individual word and characteristics of that word. By including text–grammar variables in their regression analysis, Just and Carpenter (1980; Chapter 17 in this volume) account for some of the fixation duration variance due to such higher levels, but they cannot allocate the extra time to specific words within the affected sector of text. That is just as one would expect.

### B. Speech Recoding and the Acoustic Buffer

A second factor that may free the mind from direct control by the eye is speech recoding. Speech recoding appears to be fast and automatic; if so, the speech code might conceivably replace the visual code in subsequent processing. As we know, the acoustic loop can hold several words, so the eyes could be dwelling on one word while the mind works on an earlier word or phrase.

### C. Do the Buffers Decouple the Eye and Mind?

The speech code, the conceptual buffer (backed up by working memory), and the visual buffers constitute a system of buffers that permit the mind to be decoupled from the eyes. The ease of RSVP reading, in which each word is seen for a fixed and (in my work) equal time, is consistent with such partial decoupling. Nevertheless, the impressive success of models such as that of Just and Carpenter (as well as the work of Rayner, McConkie, and many others) shows that readers ordinarily do choose to look at the words most relevant to what they are thinking about. As Just acknowledges, however, the faster processes and those that cannot be readily allocated to single words (which would include most syntactic analyses) may not be revealed by analyses of eye movements. Other techniques, possibly including RSVP, may be necessary to study those processes (e.g., Forster, 1970; Forster & Ryder, 1971; Holmes & Forster, 1972; Holmes, 1973).

## VII. Conclusion

In conclusion, the comparison of eye movements in reading, picture viewing, and visual search has shown that the obvious differences are accompanied by important similarities. I have focused here on one of these "similarities with a difference," the existence and nature of buffers or intermediate representations between the eye and the mind, and between the mind and the next eye movement. Further research could profitably address some of the open questions about the time course and character of such representational systems.

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