Eye Movement Control During Visual Object Processing: Effects of Initial Fixation Position and Semantic Constraint

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Abstract Eye movement patterns were recorded while subjects viewed arrays of line drawings of objects. The initial landing position of the eyes on an object was found to be normally distributed around the center of the object, with the modal landing position at the center. Landing variability was greater in the direction of the eye movement vector than in the direction perpendicular to the movement, and there was more of a tendency to undershoot the center of the object than to overshoot it. Landing position was found to influence other aspects of eye movement behaviour. The duration of the first fixation on an object decreased and the probability of refixating an object increased as the deviation of the initial landing position from the center of the object increased. The effect of a cognitive factor, semantic constraint, was also examined. Landing position and semantic constraint were found to interact such that semantic constraint had a greater effect the further the eyes landed from the center of the object. The results are discussed in terms of their implications for the use of eye movement behaviour as an indicator of perceptual and cognitive processing.

Résumé On enregistrait les mouvements oculaires des sujets pendant qu'ils regardaient des rangées de dessins d'objets. Le point de fixation initial des yeux sur un objet était normalement distribué autour du centre de l'objet, avec le point de fixation modal au centre. La variabilité de la fixation était plus grande dans la direction du vecteur du mouvement oculaire que dans la direction perpendiculaire au mouvement et il y avait une tendance plus grande à sous-estimer plutôt qu'à surestimer le centre de l'objet. L'endroit de fixation influençait les autres aspects du comportement oculaire. La durée de la première fixation sur un objet décroissait et la probabilité de fixer à nouveau un objet augmentait au fur et à mesure qu'augmentait la déviation du point de fixation initial. Les effets d'un facteur cognitif, la contrainte sémantique, ont aussi été examinés. L'endroit de fixation et la contrainte sémantique montraient une interaction de façon telle que la contrainte sémantique avait un plus grand effet lorsque les yeux atterrissaient plus loin du centre de l'objet. Les résultats sont discutés sous l'angle de leur implication lors de l'utilisation du mouvement oculaire comme indicateur du traitement perceptuel et cognitif.

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The use of eye movement behaviour as a dependent measure has recently provided a great deal of useful information about basic processes in complex visual tasks such as reading (e.g., Just & Carpenter, 1987; Rayner, 1978; Rayner & Pollatsek, 1989) and picture processing (e.g., Antes, 1974; Loftus, 1972; Mackworth & Morandi, 1967; Rayner, 1978; Yarbus, 1967). However, it has also become clear that if eye movement behaviour is to realize its full potential as an on-line measure of perceptual and cognitive processes, a more thorough understanding of eye movement control and of the factors that influence the eye movement pattern will be necessary (Rayner & Pollatsek, 1989). While much of the recent work on eye movement control has been concerned with eye movements during reading (Henderson & Ferreira, 1990; McConkie, 1979; McConkie & Zola, 1984; Morrison, 1984; Pollatsek & Rayner, 1982; Pollatsek, Rayner, & Balota, 1986), a complete model of eye movement control will have to generalize across visual-cognitive domains (Henderson, 1992b). The present study was designed to examine basic eye movement behaviour in a complex visual task other than reading. The goals were, first, to add to the data-base concerning eye movement behaviour, and second, to determine whether results obtained in reading would generalize to another task. To these ends, eye movement behaviour was examined while observers viewed arrays of line drawings of objects.

An example of eye movement behaviour observed in a complex task is the tendency for the initial landing position (or *preferred fixation location,* Rayner, 1979) following a saccade to be at or slightly to the left of the center of a target word when the word is to be identified (Dunn-Rankin, 1978; Hyona, Niemi, & Underwood, 1989; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1981; Rayner, 1979). One hypothesized explanation for the position of the preferred fixation location is that the *convenient viewing position* (O'Regan, 1981), or optimal position for inspecting and identifying a word, tends to be near the center of a word. The first issue addressed in the present study was whether a preferred fixation location and a convenient viewing position would also be found in a complex visual-cognitive task involving the recognition of objects instead of words.

The second issue addressed in the present study was the degree to which the initial landing position on an object affects various other eye movement behaviours, specifically *first fixation duration* (the duration of the initial fixation following a saccade to the stimulus, but excluding subsequent fixations within the stimulus), and *probability of refixation* (the probability of fixating the stimulus again immediately following the initial fixation on the stimulus). Measures based on these eye movement behaviours are often used by researchers interested in the visual-cognitive processes involved in word and object identification, as well as higher level cognitive operations. On one view, first fixation duration provides the most accurate reflection of word or object identification processes because it taps the earliest stages of stimulus processing (Henderson, Pollatsek, & Rayner, 1987; Inhoff, 1984). On the other hand, it has been suggested that the duration of the first fixation is primarily due to landing position (O'Regan & Levy-Schoen, 1987), so that the further the eyes land from the convenient viewing position of the target stimulus, the shorter the initial fixation and the more likely a refixation will be (O'Regan & Levy-Shoen, 1987; O'Regan, Levy-Shoen, Pynte, & Brugillere, 1984). The implication is that first fixation duration is a poor reflection of cognitive processes (O'Regan & Levy-Shoen, 1987). Indeed, it has been argued that *gaze duration* (the duration of all fixations on a word or object prior to the first saccade that leaves the word or object), which is correlated with refixation probability, provides the more appropriate measure of cognitive processing (Just & Carpenter, 1980). An important question, then, is the extent to which variations in eye movement behaviours are due to lower level perceptuo-motor factors such as landing position.

Finally, the third issue examined in this study was the extent to which higher level processes influence eye movement behaviour given the landing position of the eyes. This issue is important because most studies that employ eye movement behaviour as a measure of cognitive processing do not take into account lower level factors such as initial landing position. For example, in the scene processing literature, several studies have used fixation time measures to examine the effects of semantic constraint on object identification (e.g., Antes & Penland, 1981; De Graef, Christiaens, & d'Ydewalle, 1990; Friedman, 1979; Loftus & Mackworth, 1978; see Henderson, 1992b). In these studies, the landing position within an object has not been examined. As mentioned above, it has been suggested that if landing position is found to influence some eye movement measure (e.g., first fixation duration) more than others, then that measure will not provide a useful reflection of higher level cognitive factors (O'Regan & Levy-Shoen, 1987). On the other hand, it is possible that an eye movement behaviour found to reflect landing position will be a behaviour modifiable by several levels, and will therefore also reflect other factors in addition to landing position. In order to investigate this issue, the present study examined the combined influence of landing position and semantic constraint on several eye movement behaviours associated with fixation time on an object.

In summary, the present study re-analyzed a subset of the data presented by Henderson, Pollatsek, and Rayner (1989, Experiment 3) in order to examine three questions concerning eye movement behaviour. First, where within an object do the eyes tend to land following a saccade to that object? Second, what effect does a particular landing position have for subsequent eye movement behaviour on the object? Third, how does landing position affect the influence of a cognitive factor on eye movement behaviour? In order to explore these questions, subjects were presented with rectangular arrays of four line drawings of objects. The subjects were instructed to look at each of the objects in a prescribed sequence to prepare for an immediate probe memory task, and their eye movements were recorded as they examined the arrays (Henderson et al., 1987, 1989).

METHOD

Subjects

Ten members of the University of Massachusetts community were paid to participate in the experiment. The subjects all had experience with other eye movement studies, and were naive with respect to the purpose of the experiment.

Materials

Eighty line drawings of common objects (primarily taken from Snodgrass & Vanderwart, 1980) were used as stimuli in the experiment. The line drawings were entered into the computer via a Summagraphics Bit-Pad. The objects were combined into 100 displays, each containing 4 objects. The objects in each display were centered on the corners of an imaginary square, with about 5 degrees of visual angle between the centers of any two adjacent objects. In addition, a pattern mask composed of irregularly drawn line segments was employed.

Five lists of 20 displays each were constructed such that (1) four displays in each list contained 4 semantically related objects while the other 16 lists contained 4 semantically unrelated objects; (2) each object appeared in one display in every list, and always with 3 new objects; and (3) each object always appeared in the same location within a display across lists. The displays were randomly ordered within lists for each subject, and two practice trials containing objects not used in the test displays were added at the beginning of each list[1].

Apparatus

The stimuli were displayed on a Hewlett-Packard 1300A cathode ray tube (CRT) with a P-31 phosphor. Removing a point on the CRT resulted in a drop to 1% of maximum brightness in 0.25 ms. A black theater gel covered the CRT so that the display appeared clear and sharp to the subjects. A bite bar was used to eliminate head movements.

Eye movements were monitored via a Stanford Research Institute Dual

1 In the Henderson et al. (1989) study, five display conditions were employed. However, only two of these provided an extrafoveal preview of the object about to be fixated next, one in which all four objects were displayed throughout the trial, and another in which the object currently fixated and the object about to be fixated next were displayed, but the other two objects were replaced by pattern masks. Because the issue of interest here concerns landing position on an object that was visible prior to the saccade, the data reported include only these two conditions, which are not treated separately.

Purkinje Eyetracker with a resolution of about 10 minutes of arc. The eyetracker and CRT were interfaced with a Hewlett-Packard 2100 computer which controlled the experiment. During the experiment, the computer kept a complete record of the subject's eye movement behaviour, including individual fixation positions and fixation durations. The signal from the eyetracker was sampled every 1 ms by the computer and the position of the eye was determined every 4 ms. Eye movements were monitored from the right eye, though viewing was binocular.

The subject's eyes were 46 cm from the CRT and each object subtended approximately 2 degrees of visual angle both horizontally and vertically. The pattern mask employed was slightly larger than the largest object. The room was dark except for a dim indirect light source.

Procedure

Before the experiment, subjects were presented with each object one at a time on the CRT, and were asked to name each one. If necessary, the experimenter corrected the name employed by the subject to prevent confusion later in the experiment. The eye movement system was then calibrated in both the horizontal and vertical dimensions. After calibration, five blocks of 22 trials were given. The first 2 trials of each block were practice and were not scored. The next 20 trials of each block constituted the test trials.

A trial consisted of the following events: First, a central fixation cross appeared, and the calibration was checked by examining the position of a second cross which moved with the eye. If the calibration was satisfactory, the experimenter warned the subject that the trial was to begin, and approximately 250 ms later the fixation and calibration crosses were replaced by a display. The subject then made a saccade from the center of the display (where there was no object) to the upper left position, and thereafter looked around the display in a counter-clockwise direction in order to see which objects were there. All subjects found the prescribed order in which to view the four objects easy and natural to follow. The subjects were told that they could look back to an object if necessary, but were encouraged to maintain the prescribed viewing order if possible.

The subject was asked to depress a display termination key once he or she had identified the objects in the display. This caused the objects to be replaced by a display containing 4 pattern masks, one in each object position, for 500 ms. These masks were used in order to make it impossible to answer the probe question on the basis of phosphor persistence. The experimenter then asked the subject whether a particular object had appeared in this display. Half of the questions required a "yes" response. On the "yes" trials, each of the four object positions were queried about equally often. Subjects had no difficulty answering these questions correctly. Further details of the procedure may be found in Henderson et al. (1989).

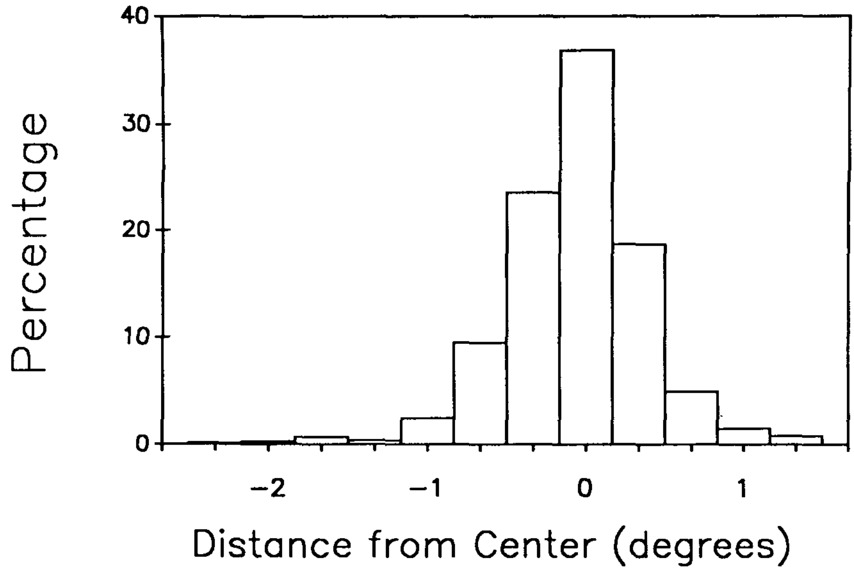

Fig. 1 Histogram showing the dispersion of the initial landing position of the eyes parallel to the eye movement vector.

RESULTS

The following analyses are based upon eye movement behaviour during fixations on the objects occupying the second and third quadrants of the displays. Data based on the objects occupying the first quadrant were excluded because saccades to those objects were necessarily shorter and were initiated from a location that did not contain an object. Data based on the objects occupying the last quadrant were excluded because fixation time on them was terminated by a manual button press. Approximately 2% of the potential data points from the two scored quadrants were discarded either because the eyetracker lost track of the eye, or because no fixations occurred within the quadrant.

Initial landing position

Figures 1 and 2 show the frequency of landing at a given distance from the center of the objects. These data are based on the initial landing position within a quadrant. Figure 1 shows landing dispersion around the center of the object parallel to the eye movement vector, while Figure 2 shows landing dispersion orthogonal to the eye movement vector. For parallel dispersion, a negative distance from the center indicates that the landing position was closer to the launch point of the saccade. For orthogonal dispersion, a negative distance indicates that the landing position was closer to the inside of the display.

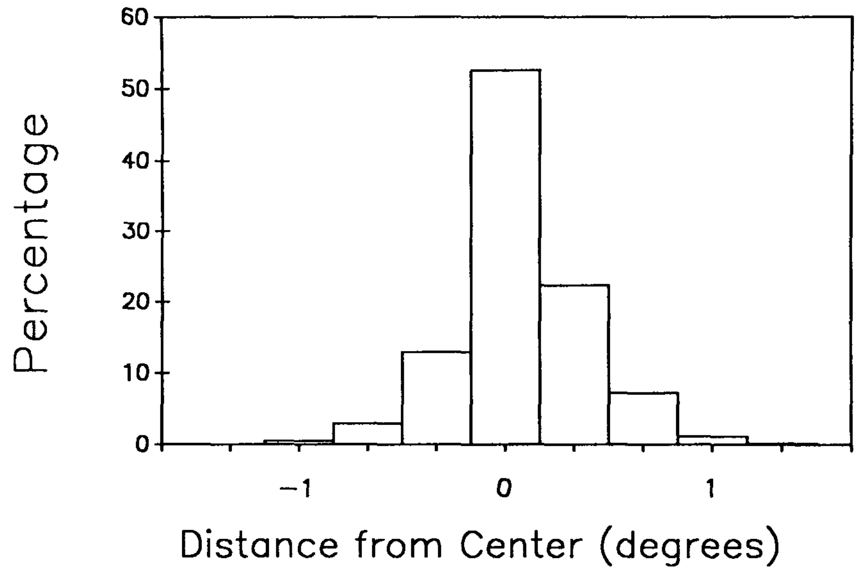

Fig. 2 Histogram showing the dispersion of the initial landing position of the eyes perpendicular to the eye movement vector.

As can be seen in Figure 1, subjects were quite accurate at directing their eyes the appropriate distance to the objects. Overshoots and undershoots (initial landing positions greater than or less than 1 degree from the center of the object) occurred on only 2% of the trials. The modal landing position was the center of the object (39% of the trials), and 79% of all landings were within plus or minus 20 minutes of arc to either side of the center. The distribution of landing positions around the center was relatively normal, with some tendency for the eyes to undershoot rather than overshoot (37% vs 26%).

As Figure 2 shows, accuracy along the dimension orthogonal to the eye movement vector was less variable than accuracy along the parallel vector. Orthogonal dispersion virtually never lead to lateral misses of the object (initial landing positions greater or less than 1 degree of arc from the center of the object). The modal landing position was again the center of the object (53% of the trials), and 88% of all landings were within 20 minutes of arc to either side of the center. The distribution of landing positions was relatively normal, with a greater tendency for the eyes to land toward the center of the display than toward the outside (31% vs 16%).

The landing position distributions indicate that the preferred fixation location on an object is the center of the object. This is consistent with the data from reading (Rayner, 1979) and indicates that during complex visual-cognitive tasks, observers prefer to place their eyes near the center of an attended stimulus. The bias toward landing nearer the takeoff position of the saccade is also consistent with the word recognition data. However, in reading the leftward bias sometimes leads to a shift in the modal landing position rather than a skew in the distribution (Rayner, 1979).

Two hypotheses have been proposed as explanations for the leftward landing bias on words during reading. According to the lexical hypothesis, initial landing position on a word tends to be to the left of center because words tend to contain more useful information at their beginnings rather than at their ends (Hyona et al., 1989; O'Regan, et al., 1984). Alternatively, according to the perceptuo-motor hypothesis, during reading the eye movement system attempts to place the fixation point at the center of each word; however, because perceptuo-motor factors can cause chronic undershoot or mislocation of the center (Findlay, 1982), the modal landing position is biased away from the center and toward the sacadic takeoff position. The results shown in Figure 1 could be taken to argue against the perceptuo-motor hypothesis, because here the modal landing position was clearly the center of the object.[2] Alternatively, it could be argued that the skew found in this experiment is a more modest form of the modal shift observed with words and is due to the same perceptuo-motor process. Because a leftward shift in the mode is not always observed in reading, and because there is evidence that the leftward bias that is observed may be due to perceptuo-motor factors (McConkie et al., 1989), the most parsimonious explanation would seem to be the latter.

Effects of Initial Landing Position

The following analyses explored the effect that initial landing position on an object has on subsequent eye movement behaviour on that object. In these analyses, overall distance from the center of the object was employed as the independent variable. It should be remembered that fixations within plus or minus 1 degree were generally within an object, and fixations beyond 1 degree were always outside of an object.

Figure 3 presents the duration of the initial fixation (first fixation duration) on an object as a function of the distance of the initial fixation from the

2 It could be argued that the examination of fixation positions collapsed over Quadrants 2 and 3 is an inappropriate comparison to the word recognition and reading studies because word studies have only used horizontal saccades, while the present study collapsed horizontal left-to-right saccades (saccades to Quadrant 3) with vertical top-to-bottom saccades (saccades to Quadrant 2). In order to determine whether a leftward shift in the modal fixation position would still be found for object stimuli given that only left-to-right saccades brought the eyes to the object, the initial landing positions in Quadrant 3 were examined separately. The data were essentially the same as those shown in Figure 1: The modal landing position was the center of the object, and there was a greater tendency to undershoot that to overshoot. Thus, it appears that the lack of a shift in the modal landing position during object fixation cannot be attributed to saccadic direction.

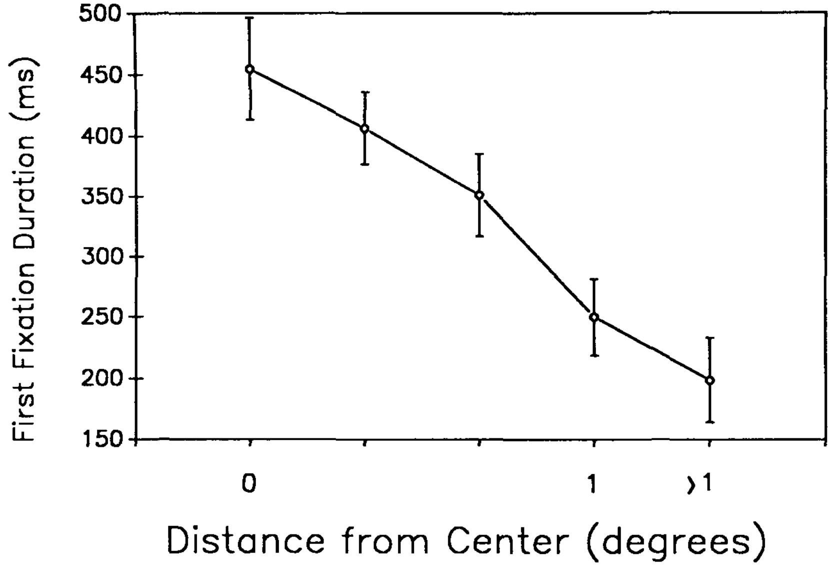

Fig. 3 First fixation duration (in ms) on an object as a function of the distance of the initial fixation from the center of the object. Error bars indicate the standard error of the mean.

center of the object. As can clearly be seen, the duration of the first fixation decreased with the distance of the landing position from the center. An Analysis of Variance (ANOVA) conducted on the data from the four locations within the object showed that the effect was reliable, $F(3,27) = 10.8$, $p < .001$. (There were not enough data points from the locations beyond the object to be included in the ANOVA.) When the initial fixation location was at the center of the object, mean first fixation duration was about 430 ms. When the initial fixation position was 1 degree from the center (which roughly corresponded to the outer edges of the objects), first fixation duration dropped to about 250 ms, and when the initial fixation did not fall on the object, first fixation duration further dropped to about 200 ms.

Figure 4 presents the probability of a second consecutive fixation within a quadrant as a function of the distance of the initial landing position from the center of the object. As was found with first fixation duration, the probability of refixating an object was related to the distance of the landing position to the center, although here the relation was positive. An ANOVA conducted on the four locations within the object indicated that the effect was reliable, $F(3,27) = 13.2$, $p < .0001$. When the initial landing position was on the center of the object, the probability of refixating the object was 16%. When the initial landing position was 1 degree from the center, the probability of refixating increased to 55%. Finally, when the initial landing position was not on the object, the probability of refixating rose to over 90%.

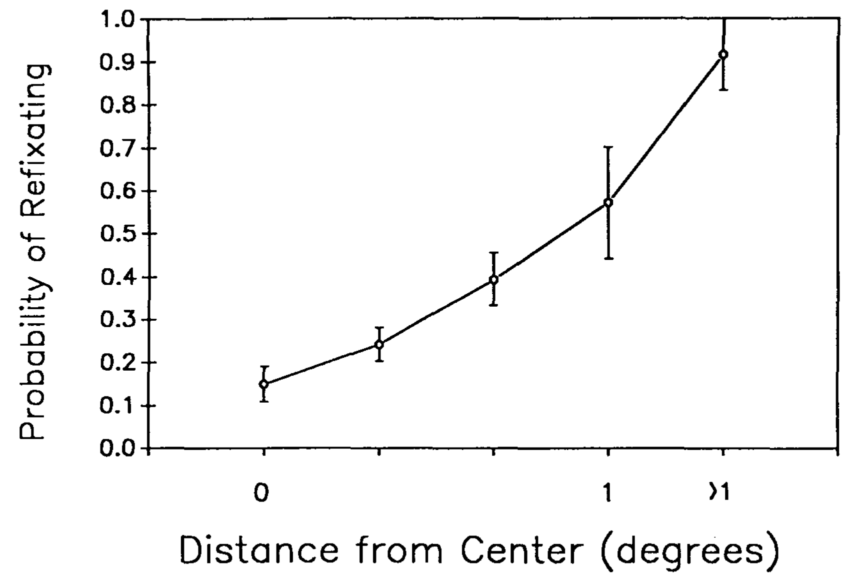

Fig. 4 Probability of refixating an object prior to leaving the object quadrant as a function of the distance of the initial fixation from the center of the object. Error bars indicate the standard error of the mean.

Figure 5 presents the duration of the refixation immediately following the first fixation on the object (given that such a refixation occurred) as a function of the distance of the initial landing position from the center of the object. Unlike the first fixation duration and probability of refixation data, there was no obvious simple linear relationship between the distance of the first fixation from the center and the duration of a subsequent fixation, though again an ANOVA conducted on the four locations within the object indicated that the differences were reliable, $F(3,27) = 4.04$, $p < .025$. An ANOVA excluding the zero location but including the other three locations within the object indicated that refixation durations increased as a function of distance, $F(2,18) = 3.72$, $p < .05$.

Taken together, the first fixation duration and probability of refixation data indicate that the initial landing position of the eyes has an immediate effect on eye movement behaviour. As the distance of the landing position from the center of the object increases, the duration of the first fixation decreases and the probability of refixating the object increases. These data essentially replicate the findings of O'Regan & Levy-Shoen (1987) and McConkie, Kerr, Reddix, Zola, & Jacobs (1989) where words were used as stimuli. The duration of a refixation on an object also tended to increase as the distance of the initial fixation on the object increased from the center, although refixations following an initial fixation on the center of the object tended to be longer than would be predicted from such a function.

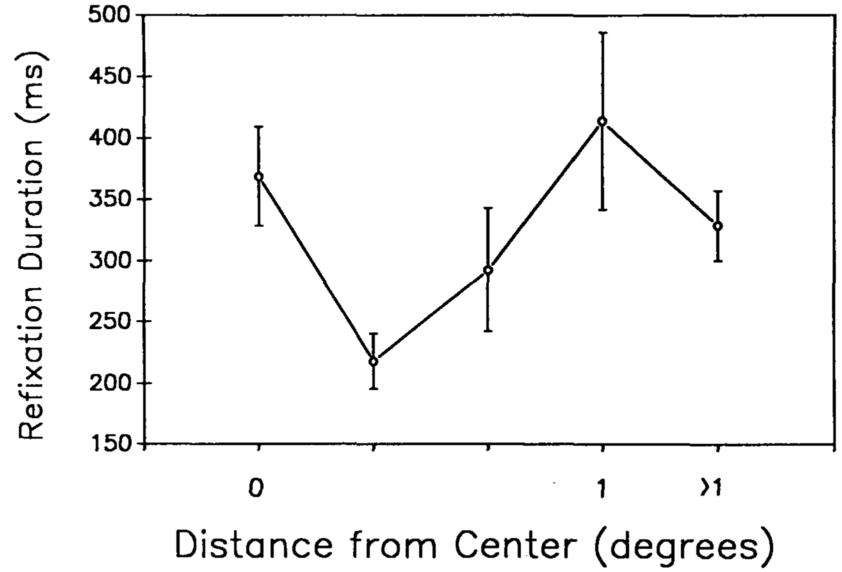

Fig. 5 Duration of the refixation on an object (in ms) given that the object was refixated as a function of the distance of the initial fixation from the center of the object. Error bars indicate the standard error of the mean.

Interaction of Contextual Constraint and Landing Position

Prior studies have shown that fixation duration on an object is reduced when the object is fixated following a related object (Henderson et al., 1987, 1989). In addition, the results of one study suggested that the effects of context may be mediated by landing position. Henderson et al. (1987) used an object naming study to examine the effects of contextual constraint. Subjects were shown two objects simultaneously, one at the fovea and one extrafoveally. The subject's task was to move his or her eyes from the object shown at the fovea (context object) to the object shown extrafoveally (target object), and to name the target object once it was fixated. The target object could either be related or unrelated to the context object seen before the eye movement. In one condition, the eyes had to move five degrees from the context object to the target object, and in another condition the eyes had to move ten degrees. The result of interest here is that when the eyes moved five degrees, the initial landing position was nearly always on the object and the contextual facilitation was minimal. In contrast, when the eyes moved ten degrees, the initial landing position was nearly always off of the object and the contextual facilitation was comparatively large.

While the difference in contextual facilitation observed by Henderson et al. (1987) could be due to landing position, it could also be due to other differences correlated with the need to execute a longer saccade in the ten degree condition, such as the spatial extent or duration of the saccade, or the latency of the eye movement from the context object to the target object (see Henderson et al., 1987, for further discussion of this point). In the present study, an object was fixated following fixation on either a semantically related or semantically unrelated object. In either case, fixation on the object would follow a saccade from an object about five degrees distant. Therefore, the present study allows for a test of the hypothesis that contextual facilitation will be greater when the eyes do not land in the preferred fixation location. For these analyses, twelve of the twenty displays were used. Four of these displays contained four semantically related objects, four displays contained the objects from the second quadrant of the semantically related displays with three unrelated objects, and four displays contained the objects from the third quadrant of the semantically related displays with three unrelated objects. In addition, because of a storage-medium problem, only 9 of the original 10 subjects were available for these analyses. Because of the reduction in the number of data points, only the three landing locations closest to the center of the object are presented (distances of 0, 1/3 and 2/3 degree from center).

Figures 6 and 7 present two commonly used measures of cognitive processing, first fixation duration and gaze duration, as a function of initial fixation position and semantic relatedness to the immediately preceding object. As can be seen in the figures, there was a clear interaction of landing position and contextual constraint, such that context had a much smaller effect when the eyes landed near the center of the object, $F(2,16) = 6.24$, $p < .01$ and $F(2,16) = 5.54$, $p < .025$, for the first fixation duration and gaze duration, respectively. Finally, an additional analysis indicated that contextual constraint did not mediate the effect of landing position on the probability of refixation, $F(2,16) = 1.5$, $p < .25$.

In contrast to the view expressed by O'Regan and Levy-Shoen (1987), the conclusion here seems to be that even when a particular eye movement behaviour (e.g., first fixation duration) is highly influenced by low level factors such as landing position, higher level factors having to do with object processing may still produce observable effects on that behaviour.

DISCUSSION

Three primary results were found in this study. First, the preferred fixation location or modal landing position on a line-drawing of an object was at the center of the object. Second, several aspects of eye movement behaviour were affected by the initial landing position. In particular, first fixation duration was found to decrease as the distance of the fixation from the center increased, and the probability of refixating the object was found to increase as the distance increased. These results indicate that the convenient viewing position or position most useful for object encoding is near the center of an object. The further the initial fixation is from the convenient viewing position, the

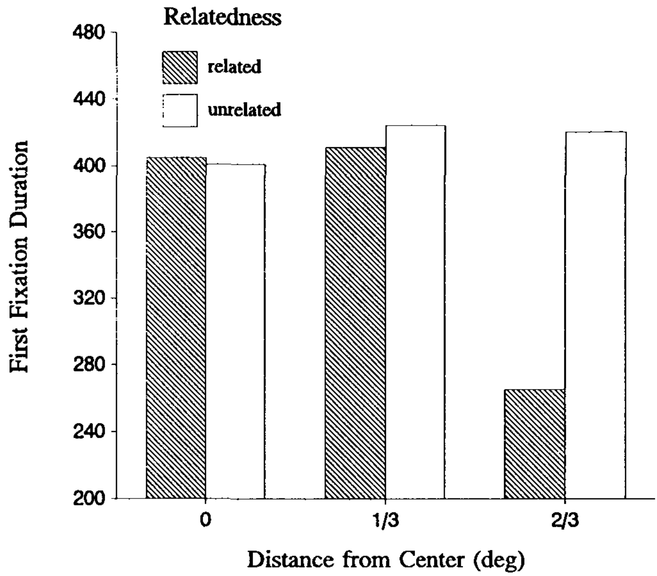

Fig. 6 First fixation duration on an object (in ms) as a function of the distance of the initial fixation from the center of the object and the semantic relatedness of the object to the object viewed in the immediately preceding quadrant.

more quickly and more likely the eyes are to refixate the object. Third, semantic constraint affected the first fixation and gaze durations on an object, particularly when the initial landing position was further from the object's center. This result suggests that eye movement behaviour reflects both perceptuo-motor and cognitive influences on object processing.

The finding that first fixation duration is influenced by landing position is interesting in light of recent discussions of the degree to which eye movement patterns can reveal higher level visual-cognitive processes such as stimulus identification. For example, it has been argued that because the duration of the first fixation is primarily determined by the distance of the fixation location from the convenient viewing position, it is therefore not a good measure for revealing cognitive processes (O'Regan and Levy-Schoen, 1987). On the other hand, many studies have shown that first fixation duration does reveal higher-level processing. In reading, for example, first fixation duration has been found to reflect both lexical (Henderson & Ferreira, 1990; Inhoff & Rayner, 1986; Rayner & Duffy, 1986) and syntactic factors (Ferreira & Henderson, 1990; Rayner & Frazier, 1987). Similarly, in picture-viewing, first fixation duration has been found to reflect the effects of semantic constraint on object processing time (De Graef, Christiaens, & d'Ydewalle, 1990; Henderson et al., 1987, 1989).

Given that initial landing position influences first fixation duration, there

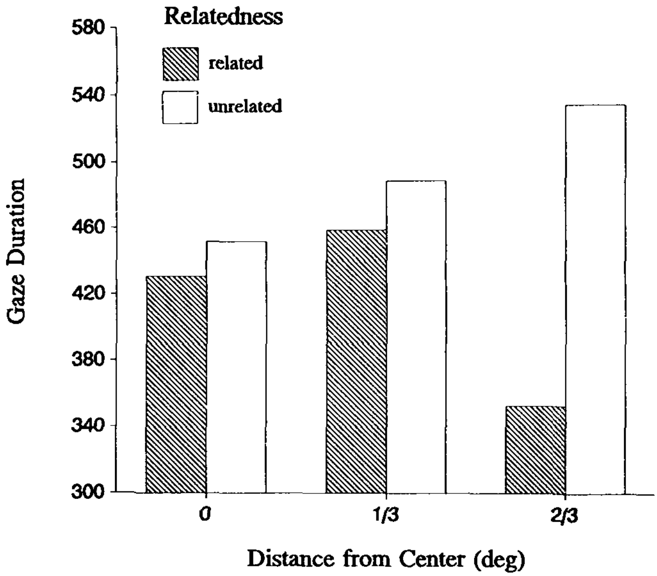

Fig. 7 Gaze duration on an object (in ms) as a function of the distance of the initial fixation from the center of the object and the semantic relatedness of the object to the object viewed in the immediately preceding quadrant.

would appear to be three possible ways in which cognitive factors could be related to first fixation duration. First, if it were the case that first fixation duration is entirely driven by perceptuo-motor factors like landing position, then it could be that cognitive processes simply are unable to influence first fixation duration. This is the view advocated by O'Regan & Levy-Shoen (1987). Second, it could be that perceptuo-motor factors control the duration of the first fixation when the initial landing position is not near the convenient viewing position, but that cognitive factors control the duration when the eyes land near the center of the stimulus. Finally, it could be that an aspect of eye movement behaviour that is under moment-to-moment control by one factor such as landing position will be an aspect of eye movement behaviour that can similarly be controlled by other factors at other levels.

The finding that first fixation duration reflected semantic constraint at the same time that it reflected landing position provides clear evidence against the view that first fixation duration will not reflect cognitive processes. Further, in contrast to the view that first fixation duration reflects visual-cognitive processes when it is least likely to reflect landing position (i.e., when the landing position is near the center of the object), it was found that first fixation duration was more likely to reflect the effect of semantic constraint on object encoding when landing position was further from the center. Finally, the effect of semantic constraint was found to be about equally robust in both the first fixation duration and gaze duration measures, suggesting that gaze duration does not necessarily provide the more valuable measure of cognitive processing (cf., Just & Carpenter, 1980; O'Regan & Levy-Shoen, 1987).

The interactive effect of landing position and semantic constraint on first fixation duration can be taken to suggest that both factors influence the same stage of processing (Sternberg, 1969). There would appear to be two stages at which the interaction could be produced. First, it could be that both factors have a direct influence on eye movement control. Second, it could be that both factors influence some intermediate stage of processing, which in turn influences eye movement control. One intermediate stage that could be influenced by both landing position and semantic constraint is object identification.

The simplest way to account for the observed interaction of semantic constraint and landing position is to assume that both semantic constraint and landing position affect object identification. The view that stimulus identification plays a large role in the decision of when to move the eyes has recently been argued by Pollatsek and Rayner (1990). On this view, only one process (identification) rather than two (identification and landing position) needs to be monitored by the eye movement control system. I have provided evidence elsewhere that object identification is affected by the semantic constraint provided by a related object viewed on the previous fixation (Henderson et al., 1987, 1989). Similarly, it is likely that landing position also influences the object identification stage, with a poorer landing position leading to a more visually degraded image. An interaction between semantic constraint and visual degration is often taken as evidence for the operation of both factors at the identification stage of processing: The information lost due to a poor landing position (visual degradation) is thought to be partially offset by the information provided by semantic constraint (Meyer, Schveneveldt, & Ruddy, 1975; Sperber, McCauley, Ragain, & Weil, 1979). A straightforward extension of this explanation, then, would be that fixation duration is controlled by the rate or usefulness of information uptake for object identification. On this view, if the initial landing position is optimal, the information will be maximally useful and the eyes will remain at that location until object identification is complete. Further, because the quality of the visual information is high, semantic constraint will not play much of a role. If, on the other hand, the eyes do not land at the convenient viewing position, the quality of information will be lower, and the eyes will be programmed to refixate the object as quickly as possible. So far, this model predicts longer first fixation durations, lower probability of refixating, and little effect of semantic constraint when the eyes land at the center, and shorter first fixation durations when the eyes land away from the center. However, because semantic constraint should increase the usefulness of the available visual information when the eyes do not land at the center, the first fixation duration should increase when the semantic constraint is helpful. Instead, the data indicate that the duration of the first fixation was *shorter* given helpful versus unhelpful semantic constraint when the eyes land away from the center.

A simple model of eye movement control based on the view that first fixation duration is determined by monitoring the object identification process does not seem able to account for the present data. The general finding has been that when the stimulus is degraded, there is more effect of semantic constraint, and processing time is longer. In the present study, when the stimulus was degraded, processing time was *shorter*. It therefore appears that a model that is able to account for the effects of both landing position and semantic constraint will have to assume that eye movements are controlled both by the success of object identification processes and by independent information about the distance of the fixation position from the convenient viewing position. For example, in the present study it could be that semantic constraint and landing position interact within the object identification processor as discussed above (context has a greater influence given a poor landing position and thus degraded input). The eye movement control system would monitor the ongoing identification process. At the same time, landing position would be monitored independently such that the greater the discrepancy between the convenient viewing position and the landing position, the greater the probability and more quickly a corrective movement will be programmed. On this model, the independent monitoring of the landing position leads to the overall shorter first fixation duration and greater probability of refixating the object when the eyes land away from the preferred viewing position. This effect is added to the interaction of semantic constraint and landing position. Thus, semantic constraint has a greater influence when the landing position is poor, but because the eyes are sometimes moved by the error correction system before identification is complete, the mean duration of the first fixation is shorter overall when the eye lands away from the convenient viewing position.

So far, both the first fixation duration and probability of refixation data are accounted for in a straightforward manner. The final pattern of data to examine is the gaze duration data. First, the interaction between semantic constraint and landing position can be explained in the same manner as the first fixation duration and probability of refixation data. However, another aspect of the gaze duration data presents somewhat of a puzzle. If it is the case that the time spent on an object is ultimately a function of the time needed to identify the object, then gaze duration on an object should be shorter when the landing position is near the center of the object compared with when it is further from the center. Contrary to this prediction, gaze durations were shortest in the far landing position, semantically related condition. How can this pattern be explained?

A likely explanation would appear to be that multiple fixations on an object are inherently more useful than a single fixation (Loftus, 1972). For example, two fixations of 200 ms each might be more useful than a single fixation of 400 ms. This would be true if the rate of information uptake decreased over the course of the fixation, perhaps because the same parts or features of the object continue to receive foveal processing in the single fixation case (Loftus, 1983). Thus, the gaze duration pattern can be explained by assuming that during each fixation semantic constraint will interact with landing position as described above, but in addition, each new fixation will further increase the efficiency of processing the object.

Conclusion

The important implication of these results is that first fixation duration, probability of refixation, and gaze duration provide a reflection of the difficulty of visual-cognitive processes. Particularly in the case of first fixation duration, this conclusion is true even though landing position also exerts a large influence. In addition, a clear implication of these results is that when looking for cognitive level effects, it may be worthwhile controlling the distance that the subject lands from the center of the object as a way to decrease the variability due to lower level perceptuo-motor factors.

In conclusion, the eye movement behaviour described here is in many ways similar to eye movement behaviour observed in reading. Further specification of the similarities and differences in eye movement behaviour across visual-cognitive tasks will allow construction of a more complete model of eye movement control, which will in turn provide new insight into visual cognition and reading. An important implication of the results reported here is that eye movement behaviour that is clearly affected by perceptuo-motor factors can still provide a useful measure of higher-level cognitive processes.

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