Research Article

Eye Movements Do Not Reflect Retrieval Processes
Limits of the Eye-Mind Hypothesis

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ABSTRACT
This research investigated whether eye movements are informative about retrieval processes. Participants learned facts about persons and locations, and the number of facts (fan) learned about each person and location was manipulated. During a subsequent recognition test, participants made more gazes to high-fan facts than to low-fan facts, and gazes to high-fan facts had a longer duration than gazes to low-fan facts. However, there was no relation between the order in which items were fixated and the relative effect of person or location fan. The effect of person and location fan on gaze duration also did not differ with whether it was the person or location being fixated. A model assuming that the process of retrieval is independent of eye movements was successfully fit to the data on the distribution of gaze durations. According to this model, the effect of fan on number of gazes and gaze duration is an artifact of the longer retrieval times for high-fan facts.

Can memory retrieval be studied by tracking where participants fixate and how long they dwell at various locations? Eye movements can reveal a great deal about underlying cognitive processes (Just & Carpenter, 1984; Rayner, 1995, 1998). The eye-mind hypothesis (Just & Carpenter, 1984) states that there is a strong correlation between where one is looking and what one is thinking about. In the reading literature, duration of gaze on individual words and number of regressions to words reflect the difficulty in processing those words and the processing of sentence structure (e.g., Just & Carpenter, 1984; Mak, Vonk, & Schriefers, 2002; Reichle, Pollatsek, Fisher, & Rayner, 1998). Similarly, duration of gaze on words presented to participants as memory prompts might reflect on the retrieval of memories cued by these words.

The fan paradigm (e.g., Anderson, 1974, 1976) is a good choice for using eye movements to study retrieval. The experiment reported here is closely based on a previous study (Anderson, 1974) in which participants studied groups of sentences like the following:

1. The doctor is in the bank. (1–1)
2. The fireman is in the park. (1–2)
3. The hippie is in the church. (2–1)
4. The hippie is in the park. (2–2)

The two numbers in parentheses following each statement indicate the number of facts, or *fan*, associated with the person and the location, respectively. For instance, in this example, Sentence 3 is labeled "2-1" because its person occurs in two sentences

(Sentences 3 and 4) and its location in just one (Sentence 3). In this paradigm, after participants study a group of sentences, they are mixed in with foil sentences that consist of the same concepts but in different combinations; the task is to identify which sentences were presented during the study phase. Reaction times demonstrate a *fan effect*: Participants are slower to recognize facts or foils composed of higher-fan concepts than those composed of lower-fan concepts.

These effects have been used to study effects of aging (Radvansky, Zacks, & Hasher, 1996), working memory capacity (Cantor & Engle, 1993), and frontal lobe damage (Kimberg, 1994), as well as metamemory judgments (McGuire & Maki, 2001). Results involving the fan effect played an important role in the original development of the human associative memory (HAM) theory (Anderson & Bower, 1973) and in the formulation of the adaptive-control-of-thought (ACT) theory (Anderson, 1976, 1983). The fan effect is generally conceived of as having strong implications for how retrieval processes interact with memory representations.

This paradigm seemed ripe for eye movement analysis. One can vary the difficulty posed by individual words in the sentences by manipulating their fan, and one might expect longer fixation durations for high-fan than for low-fan words. Moreover, the exact pattern of effects might reflect the underlying retrieval processes. For instance, it might discriminate between single-access models and multiple-access models. According to single-access models (e.g., Myers, O'Brien, Balota, & Toyofuku, 1984), participants use one word (person or location) to retrieve sentences from memory and see if they can retrieve something that matches the full sentence probe. According to multiple-access models (e.g., Anderson, 1976, pp. 275-278), participants retrieve information from multiple concepts simultaneously, looking for an intersection. If eye movements reflect retrieval, a single-access model predicts that participants would be affected by the fan of the first word they encode because they can initiate retrieval from it. In contrast, a multiple-access model (e.g., Anderson, 1976) predicts that there would not be any fan effects until both person and location have been encoded. In addition to duration of gaze, gaze order might be informative. Participants could fixate the items in the order person-location or location-person, and fan effects might depend on the order in which the words are fixated.

Being able to use eye movements to help identify the nature of the retrieval process depends on one critical assumption, however--that participants' fixation durations reflect retrieval processes. This goes to the eye-mind assumption underlying the use of eye movements to study cognition. Although participants in this paradigm need to look at the words to encode them to initiate retrieval, it is possible that the gaze durations are unrelated to retrieval. In high-fan conditions, there might be more gazes, rather than longer gaze durations. A number of studies have shown a relationship between where a participant looks and memory (e.g., Loftus, 1972; Parker, 1978; Richardson & Spivey, 2000). Loftus found a relation between number of fixations on an object and subsequent recall, but no effect of the duration of the fixations. However, these studies did not investigate whether there is a relation between duration of a gaze and difficulty of retrieval.

We coalesced these ideas into three models, which were our alternative hypotheses when we began the research:

Single-access model

The duration of the first gaze reflects how long that retrieval takes and therefore the fan of that element. The subsequent gaze checks the other element to determine if it matches the memory retrieved, and so its duration does not reflect fan.

Multiple-access model

Because retrieval can be initiated only after both person and location have been encoded, there is no effect of fan on duration of first gaze. However, duration of the second gaze reflects the fan of both elements.

Independence model

This model assumes that participants need to fixate both elements in order to encode the words, but that eye movements do not reflect retrieval processes taking place after encoding. Therefore, fan has no effect on the durations of the gazes, but does affect the number of gazes.

The single-access and multiple-access models both imply that the modal number of fixations should be two (one on each word), whereas the independence model implies that there are more than two.

EXPERIMENT

This experiment was designed to replicate the original fan experiment (Anderson, 1974) with collection of eye movement data. Pilot research had shown that participants tended to look only at the person and location in the sentences. Therefore, our probes presented the person and location only--one on the left side of the visual field and the other on the right side. Because we were interested in the effects of fan of the first element fixated, and because order of presentation might affect which element was fixated first, we included two conditions that differed in whether the presentation order was person-location or location-person. Multiple successive fixations on the left or right terms were aggregated. Such aggregate fixations are called *gazes* in the reading literature (e.g., Rayner, & Pollatsek, 1989), and we continue that convention. Gaze times have proven to be good measures of word difficulty in reading (Reichle et al., 1998).

Method

Participants

Seventeen participants were in the person-location group and 18 in the location-person group. They were recruited for pay from the Carnegie Mellon University community.

Materials

Twenty-eight person-location sentences (facts) were randomly generated for each participant from a set of 17 person nouns and 17 locations. These instantiated all possible combinations of person fan (from 1 to 3) and location fan (from 1 to 3), just as had the

original (Anderson, 1974) experiment. There were three instances of each combination except for 2-2, for which there were four. An equal number of foils instantiating all the combinations were created as well. Foils were created by randomly re-pairing the persons and locations within one of the cells in the 3 x 3 design. A block in the recognition phase consisted of the 28 targets and 28 foils, for a total of 56 trials. There were six recognition blocks, for a total of 336 trials.

Procedure

As in the original study (Anderson, 1974), participants were drilled in answering questions of the form "Where is the person?" and "Who is in the location?" until we were satisfied that they knew the material. The critical recognition phase followed. In this phase, only the person and location words were presented. One word was 5° left of the center and the other 5° right of center, for a separation of 10°. The words themselves subtended 2° to 3° of visual angle. This was the only phase of the experiment in which the participants were monitored by the eye movement equipment. Participants responded to each probe by pressing a key ('k" for "yes," "d" for "no"). Between blocks, participants were given a chance to take a short break, and the equipment was recalibrated if necessary. The eyetracker used to determine participants' point of regard (POR) during the trials was an ETL-500, manufactured by ISCAN, Inc. (Boston, Massachusetts). POR data were recorded every 16.7 ms by the experiment delivery software. We have found that with this equipment and this frequency of recalibration, we can keep the error of estimation of POR to under 1° of visual angle.

Design and Analysis

All data were analyzed according to 2 x 2 x 3 x 3 design in which the factors were the between-participants factor of order of presentation (person-location or location-person) and the within-participants factors of target versus foil, person fan, and location fan. A number of dependent variables were analyzed in this design. They included the traditional measures of mean percentage correct and mean latency for correct judgments, but also a number of eye-movement-based measures.

The screen was divided into a left and a right half. All fixations on the screen were classified according to which half they were in. Fixations off the screen were ignored. For purposes of analysis, multiple successive fixations on the person or location half of the screen were aggregated into a single gaze reflecting the encoding of one of the terms. In effect, every time the eye fixated on a new half of the screen, a new gaze was counted, and gaze duration was all the time spent on one side of the screen before the eye crossed the boundary. The actual response was counted as terminating the last gaze. Thus, all trials were decomposed into a sequence of one or more alternating gazes starting either with the person or the location and ending with a key press. The eye movement dependent measures were order of gazes, number of gazes, and duration of the various gazes.

Results

Participants spent almost all of their time fixating the screen. Less than 1% of the time was spent off screen. On average, 83% of the first gazes were on the left-most element. A few participants in the location-person condition showed a tendency to look at the person even though it was on the right, but this tendency was not strong enough to significantly affect the difference between the groups in the percentage of first gazes that were on the left (87% vs. 78%), $F(1, 33) = 2.17$, $p > .10$, $MSE = 0.573$. The group variable did not even approach significance for any other measure, so subsequent analyses collapse the two groups together.

Main Effects

Table 1 provides a summary of the effects of the three within-participants factors–target versus foil, location fan, and person fan. The first two dependent measures reported for each factor are the traditional ones: error rate and overall latency. The effects obtained are typical of fan experiments. In particular, participants became slower and less accurate as person or location fan increased. The difference between fans of 1 and 3 on either dimension was almost 200 ms.

The other two dependent measures reported in Table 1 are number of gazes and duration of gazes. There were significant fan effects on both of these measures. The number of gazes averaged a little more than three, but there was variability. On 1.9% of the trials, there were no gazes or only one gaze, on 25.0% there were two, on 44.2% there were three, on 15.3% there were four, on 8.2% there were five, and on 5.4% there were more. In the analyses that follow, we excluded those trials on which participants made no or one gaze and all trials on which they made errors.

Figure 1 presents gaze duration for first, second, and later gazes, collapsing over the variable of target versus foil, which did not interact with the fan effects. There were no significant effects involving first-gaze duration. The mean first-gaze durations were 400, 399, and 401 ms for location fans of 1, 2, and 3 and 399, 399, and 401 ms for person fans 1, 2, and 3. In contrast, there was a significant effect of location fan on second-gaze duration–473, 474, and 499 ms for location fans 1, 2, and 3, $F(2, 66) = 5.35$, $p < .01$, $MSE = 5,958$. Although the effect of person fan on second-gaze duration was not significant, it was in the expected direction–472, 488, and 483 ms for fans 1, 2, and 3, $F(2, 66) = 1.62$, $MSE = 8,030$. The effects of fan were larger for the later gazes. The mean times for later gazes were 404, 434, and 450 ms in the conditions with location fans of 1, 2, and 3, $F(2, 66) = 8.08$, $p < .001$, $MSE = 14,162$, and 401, 432, and 454 ms in the conditions with person fans of 1, 2, and 3, $F(2, 66) = 14.99$, $p < .0001$, $MSE = 9,962$.

The results do not correspond to the results predicted by any the three models outlined in the introduction. In contrast to the predictions of the single-access model, fan had no effect on duration of first gaze, but did have an effect on duration of subsequent gazes. The results are more consistent with the multiple-access model, but according to that model, the expected modal number of gazes would be two, not three. Also, that model predicted fan would affect the second fixation, but we got much larger effects on later fixations. The independence model is consistent with there often being more than two gazes because it predicts an effect of fan on number of gazes, but in reasoning about the independence model, we had not predicted an effect of fan on gaze duration. As it turns out, this prediction of no effect of fan on gaze duration reflected a failure on our

part to work through the details of an independence model. The complications we ignored became apparent during a consideration of the distribution of gaze durations.

Distributions of Gaze Durations

Figure 2 displays the distributions of durations for the first gazes, second gazes that did and did not end with a response, and third gazes that did and did not end with a response. Beyond the third gaze, the sample sizes became small, and some participants contributed few observations. This figure collapses the conditions into low fan (1-1, 1-2, 2-1), medium fan (1-3, 2-2, 3-1), and high fan (2-3,3-3,3-2). It also presents the predictions from a simple model that we describe later. The data in the figure are aggregated into bins of 50 ms.

With respect to first-gaze durations, shown in Figure 2a, it is striking that not only do mean gaze durations not vary with fan, but the whole distributions of durations do not vary. The first-gaze distributions show a little peak around 200 ms. These may be cases in which the participant's eyes started out on the wrong side of the screen and quickly switched to the other.

All the remaining distributions show some effect of fan, although the effect is larger for gazes that ended in a response than for those that did not. The distributions look rather ordinary except for the distribution, in Figure 2e, for third gazes that ended in a response. All the other distributions show nearly no short durations, a quick rise to a peak, and then a long tail. In contrast, third fixations that ended in responses show a high proportion of responses at very short durations.

It turns out that these are the kinds of distributions one would expect if the retrieval process resulting in a response progresses independently from the process that controls change of gaze. The important complication that we originally failed to consider is that these two processes were in a race to determine the next gaze. Sometimes the retrieval process concluded before the gaze changed, resulting in the distributions in Figure 2c (durations for second gazes that ended in a response). Sometimes the gaze concluded first, resulting in the distributions in Figure 2b. On those occasions when the second gaze concluded just before the response, third gazes had short durations, as shown in Figure 2e for third gazes ending in a response.

The following description elaborates the relation between eye movements and retrieval in this paradigm: Both elements (person and location) need to be encoded before the response can be emitted, and both elements needed to be fixated before they can be encoded. Thus, the initiation of the response is dependent on looking at the second word, but after this, gaze and retrieval are independent. There is no relation between fan and duration of first gaze because the duration of that gaze depends on time to encode the first element, not on retrieval. There is a relation for later gazes that do not end in a response because there is a race between these later gazes and the response produced by the retrieval process. If the response occurs first, it essentially prevents the current gaze from completing as it would have (shortly after the response, there were often eye movements to places off screen or where the feedback was presented). Thus, long-duration gazes tend to be edited out by the retrieval process, leaving only the shorter gazes. More long-duration gazes are edited out when the retrieval process is short, in conditions of low fan,

than when the retrieval process is longer, in conditions of medium and high fan. Thus, the mean duration of intermediate gazes is shorter in low-fan than in high-fan conditions.

   We decided to test whether the observed distributions of second- and third-gaze latencies could be produced by races between underlying gaze distributions and retrieval-determined response distributions. Let $g_2(t)$ and $g_3(t)$ be the underlying distributions of latencies for second and third gazes and $r(t)$ be the distribution of response latencies. The response distribution $r(t)$ will reflect time to encoding the second element, retrieve the memory, and generate a response. It will show an effect of fan, but $g_2(t)$ and $g_3(t)$ will be independent of fan and of $r(t)$. Under the critical assumption that the retrieval-determined response distribution and the gaze distributions are independent, the resulting distribution of latencies for second gazes without response is as follows:

$$nr_2(t) = \frac{g_2(t)R(t)}{\int g_2(t)R(t)dt},$$

where $R(t)$ is the survivor function (the proportion of responses longer than t). The numerator reflects the probability of a second gaze concluding at time t–the probability that the second-gaze distribution terminates at t multiplied by the probability that the response distribution has not terminated. The denominator normalizes this value by the probability that the second gaze does not end in a response.
A similar formula applies for second gazes ending with response:

$$r_2(t) = \frac{r(t)G_2(t)}{\int r(t)G_2(t)dt},$$

where $G_2(t)$ is the survivor function for the second-gaze distribution. Calculating the third-gaze distributions requires first calculating the residual response distribution, $rr(t)$. This is the distribution of response times after the second eye movement for those responses that are longer than the second fixation:

$$rr(t) = \frac{\int g_2(x)r(t + x)dx}{\int\int g_2(x)r(t + x)dxdt}$$

   The numerator integrates over all the ways a response can take t seconds after the end of the second gaze–the various combinations of the second gaze taking x ms and the response taking $x + t$ ms. The denominator normalizes this value and is equal to the denominator in the definition of $nr_2(t)$. With $rr(t)$, we can calculate the distributions for third gazes not ending in a response and third gazes ending in a response:

$$nr_3(t) = \frac{g_3(t)RR(t)}{\int g_3(t)RR(t)\,dt}$$

$$r_3(t) = \frac{rr(t)G_3(t)}{\int rr(t)G_3(t)\,dt}$$

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The 12 distributions for second and third gazes plotted in Figures 2b through 2e are the result of races among 5 underlying distributions, 2 for the two gazes and 3 response distributions for the three fans. We attempted to determine if we could estimate 5 underlying distributions that would give rise to these 12 observed distributions. Given that the data are in 50-ms bins, we used discrete approximations to these continuous equations, placing certain smoothness constraints on the underlying distributions. Figure 3 illustrates the 5 estimated distributions, and the predicted distributions are displayed in Figures 2b through 2e.

CONCLUSIONS

The point of this curve-fitting exercise is to show that a race of independent processes (i.e., gaze and retrieval) can give rise to the observed gaze-duration distributions. The degree of correspondence between predicted distributions and observed distributions is quite compelling. The implication of this demonstration is also quite compelling to us: Eye movements say nothing about the underlying retrieval process because the process controlling the switch in gazes is independent of the process controlling retrieval. This assumption makes sense of a number of features of the data:

Fan has no effect on first gaze because the decision to switch gazes does not depend on the retrieval process. Note that this means there is no evidence whether retrieval begins with the first gaze, as the single-access model claims, or with the second gaze, as the multiple-access model claims.

Fan has no differential effect on gaze duration as a function of which term is being fixated.

Order of gazes has no effect on time to retrieve the answer.

Both fans affect all later gaze durations. For those gazes that do not end with a response, this is a consequence of the race with the retrieval process.

The distributions for third gazes that end with a response (Fig. 2e) are in some sense "broken" because the distributions are the residual latencies of the losers in the race with the second gazes.

We think that in most of the cases in which eye movements have informed models of internal cognitive processing, they have done so because of the dependence of cognitive processing on encoding of information. Indeed, in this experiment, one can tell by the eye movements that participants needed to encode both items to make their judgment (almost all trials involved fixations on both words), but in this experimental task that was already self-evident.

There are situations in which eye movements seem to indicate processing downstream from initial encoding, and one can ask how these situations are different from the situation in the current experiment. For instance, in the reading literature, the time that participants look at a disambiguating region of a sentence seems to indicate the effort they are putting into disambiguation after encoding (Ferreira & Clifton, 1986; Mak et al., 2002). Perhaps participants are motivated to wait at the disambiguating region because going on would require further processing that would have to overlap with disambiguation. In contrast, in our task, looking back at the first term after encoding the second term does not add more information to process. Thus, there is no reason to wait at the first gaze, the second gaze, or later gazes for some aspect of retrieval to be completed. Therefore, these gazes are not sensitive to the ongoing retrieval process.

These results serve to refine the mind-eye hypothesis. Eye movements do not necessarily reflect mental processes, but they do reflect ongoing processes to the extent that the processes depend on the encoding of information. Although some cognitive tasks have to wait for information to be encoded, in many cases, such as the task we used in the present study, the mind has a path to travel after the encoding of the information, and eye movements do not indicate what is happening on that path.

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Fig. 1. Gaze durations in Experiment 1 as a function of location fan (1, 2, or 3), person fan (1, 2, or 3), and gaze position (first, second, third or later).

Fig. 2. Proportion of gazes in 0.05-s bins. Separate distributions are shown for first gazes (a), second gazes that did not end with a response (b), second gazes that did end with a response (c), third gazes that did not end with a response (d), and third gazes that did end with a response (e). The number of observations for each fan is about 3,500, 2,500, 1,000, 1,000, and 1,500 for the five panels, respectively. The solid lines represent the predictions from the assumed distributions in Figure 3. See the text for explanations of low, medium, and high fan.

Fig. 3. Assumed distributions of first and second gazes and retrieval distributions for the three fan conditions. Races among the gaze and retrieval distributions give rise to the observed distributions in Figures 2b through 2e.

Table 1
Main Effects on Principal Dependent Measures

(a). Target versus Foil
a. Error Rate: .058 versus .066—$F(1,33) = 1.50$, $p > .1$, MSE = .005
b. Latency: 1429 versus 1575 ms—$F(1,33) = 57.46$, $p < .0001$, MSE=58,253
c. Gaze num: 3.22 versus 3.37—$F(1,33) = 21.54$, $p < .0001$, MSE = .167
d. Gaze time: 431 versus 452 ms—$F(1,33)=29.90$, $p<.0001$,MSE=2422

(b). Location Fan (1, 2, 3)

    a.   Error Rate: .044, .063, .079—$F(2,66) = 9.01$, $p < .0005$, MSE = .007

    b.   Latency: 1404, 1508, 1592 ms—$F(2,66) = 30.06$, $p < .0001$, MSE=62,056

    c.   Gaze num: 3.15, 3.33, 3.41—$F(2,66) = 18.99$, $p < .0001$, MSE = .190

    d.   Gaze time: 432, 439, 453 ms—$F(2,66)=7.68$, $p<.001$, MSE=3440

(c). Person Fan (1, 2, 3)

    a.   Error Rate: .042, .065, .079—$F(2,66) = 8.77$, $p < .0005$, MSE = .008

    b.   Latency: 1389, 1547, 1569 ms—$F(2,66) = 23.50$, $p < .0001$, MSE=85,670

    c.   Gaze num: 3.13, 3.37, 3.39—$F(2,66) = 16.39$, $p < .0001$, MSE = .267

    d.   Gaze time: 428, 444, 452 ms—$F(2,66)=10.27$, $p<.0001$, MSE=2874