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Abstract

Two studies are reported looking at the relationship between eye movements and the fan effect. The first replicates Anderson (1974) and the second replicates Radvansky, Spieler, and Zacks (1993). These experiments require participants to judge whether they had studied a sentence asserting that a subject (person or object) is in a location. Neither experiment found an effect of fan of either subject or location on the duration of the first fixation but there is an effect of both variables on number of fixations and duration of subsequent fixations. The fan effects are the same, independent of the order in which the terms (subject and location) are presented or fixated. This is evidence for a multiple-access model that requires both terms be encoded in order to retrieve the sentence trace rather than a single-access model in which retrieval is made from one term and checked against the other. Two models are fit to these data under the assumption that, after the first fixation there is a race between a retrieval process that generates a response and an asynchronous process that generates further eye movements.

Anderson (1974, 1976) introduced a paradigm in which participants were asked to recognize multi-term sentences like "The hippie is in the park" or "The hippie touched the debutante in the park". The critical manipulation in this research varied the fan or number of facts studied about particular concepts like "hippie" and "park". The fan effect refers to the fact that latency tends to increase with the fan of facts associated with any of the concepts. The basic interpretation of this result, which has been maintained throughout the years, is that the fan effect reflected difficulties in access to these facts. As more things were associated with a particular term it became harder to retrieve the correct one. While this basic interpretation has held, there have been numerous theories about the actual retrieval processes involved (e.g., Anderson & Reder, 1999a; Myers, O'Brien, Balota & Toyofuku, 1984; Radvansky & Zacks, 1991; Reder & Ross, 1983; Smith, Adams, Schorr, 1978).

One major dimension on which these theories can be classified is whether they assume memory is accessed from multiple concepts (multiple-access assumption as was proposed originally by Anderson and Bower 1973) or just one (single-access assumption proposed for instance by Myers, et al., 1984[2]). One gets effects of the fans of all the concepts and this might seem to be evidence for multiple access. However, it is possible that on any trial participants are just accessing from one concept but vary across trials which concepts they choose to access from. That is, there might be a probabilistic mixture across trials and participants. Anderson (1976, pp. 275-278) reviewed the evidence for multiple access on a single trial. The strongest evidence may have been the min effect, which refers to the fact that, if multiple concepts have their fan manipulated, latency is more a function of the minimum fan. Even a probabilistic single-access model would not predict this because, if there was a probabilistic mixture, then on some trials it would be one concept's fan and on other trials it would be another concept's fan and there would be on average an equal effect of both fans. While the min effect does have some force in deciding this issue it is probably not decisive. One could imagine single-access models that proposed participants first tested the fan of the elements and chose to access by the low-fan item. Moreover, the min effect is not that large and given the typical error of measurement in these experiments it is always not significant. In summary, while the data may somewhat favor the multiple-access assumption, they are hardly definitive.

One problem with all of this research is that it only collects a final recognition time and does not provide any data about what is happening during that interval. The participant must in fact encode each of the terms, access memory, make a judgement, and execute a response. If one could track these subprocesses one might find more evidence about what was happening. The goal of this research is to obtain evidence about the microstructure of the process by collecting eye movements of participants while they do a fan experiment. The logic of this research is that if participants are accessing from a single concept they should show fan effects as soon as they have encoded the first item, from which they can initiate retrieval, whereas if they are accessing from multiple concepts they should show fan effects only after they have encoded all concepts from which they are accessing memory. Thus, eye movements allows one to diagnose when retrieval begins and whether both concepts have to be encoded before retrieval.

Eye-movement data provide two new types of dependent measures with which to assess fan effects. One is mean number of fixations. One might expect this variable to increase with fan just because if participants take longer they have more opportunities to move their eyes. Such a result would not discriminate between the single-access and multiple-access assumption. The other dependent measure is the mean duration of fixation. The reading literature (e.g., Just & Carpenter, 1980; Reichle, Pollatsek, Fisher, & Rayner, 1998) has found this measure to reflect difficulty of individual words and we might expect it to reflect the fan of words in our experiments. According to the single-access hypothesis, fan should affect the duration of the first fixation while, according to the multiple-access hypothesis, fan effects on fixation duration should not appear at least until the second fixation and both concepts are encoded. Furthermore under the single-access hypothesis, one might propose that the participant is retrieving from the element being fixated and so there should mainly be an effect of that element's fan. More generally, under the single-access model, we might expect different effects of fan on fixation duration depending on which element is fixated. In contrast, the multiple-access model would predict the same effect of fan no matter which element was being fixated. This paper will first present a pair of experiments showing how these dependent variables (number of fixations, duration of various fixations) relate to fan and then present a model that predicts the detailed results obtained.

While the data that from these experiments bear on the single-access versus multiple-access assumption, they also provide information about how perceptual and retrieval processes relate. Is the only role of perception in the task to encode the stimuli? Are subsequent eye movements after the initial encoding irrelevant or are they related to the retrieval process? One might think that participants would re-fixate items to help prod their memory. On the other hand, Glenberg, Schroeder, and Robertson (1998) suggest that participants need to disengage from environmental stimuli to retrieve and should either avert their gaze or at least not re-fixate stimuli. An alternative hypothesis is that there would be no relationship between eye movements and memory beyond the initial need to encode the stimuli. There are any number of imaginable relationships between fixation patterns and memory performance and we were curious about what might be the case.

Experiment 1

The first experiment was designed to replicate the original fan experiment with collection of eye-movement data. That original experiment presented the elements in the order person-location. Since interest will be in the effects of fan of the first element fixated and since order of presentation might affect which element is fixated first, we decided to also use a second condition in which the presentation order was location-person. According to the multiple-access model there should not be an effect of order of reading the elements on any variable but there could be according to the single-access model. The simplest single-access model would be one under which participants retrieved from the first element fixated and this would show an effect of the fan of the first element fixated. Subsequent fixations would be to check the result of this retrieval and might or might not reveal further fan effects.

Method

Participants. Seventeen participants were in the person-location experiment and 18 in the location-person experiment. Participants were paid for an experiment that lasted between 1 and 2 hours. The participants were paid a base $20 and then a bonus based on the score in the recognition phase. The score was 2 points for a correct answer + 1 point for each 100ms faster than 1500ms and -20 points for an incorrect answer.

Materials. Participants studied 28 person-location facts and the abstract structure of this material is illustrated in Table 1. A block in the recognition phase consisted of these 28 targets and 28 foils for 56 trials. Foils were created by randomly repairing the persons and locations within one of the cells in the 3x3 design. This guaranteed that any person or location would occur as often as a target as it did as a foil. There were 6 recognition blocks for a total of 336 trials. There were two alternative foil repairings used and these were alternated from block to block.

Procedure. The experiment had three phases, all of which were administered on a Macintosh computer. In the first phase of the experiment participants saw the 28 study sentences presented in random order. They were presented in the form "The person is in the location" for 5 seconds each, with a .5 second interval between each sentence.

The second phase of the experiment consisted of a 2-pass drop out procedure. In each pass participants received in random order all possible questions of the form "Where is the person?" and "Who is in the location?". Participants had to type in all locations associated with that person and all people associated with that location. If they were able to recall all the answers to a question that question was dropped out of the pass. If they could not, they were shown the correct answer and the question was repeated after all the other questions had been asked. This continued until all questions had been answered correctly. This whole procedure was repeated a second time so that each question would have been answered correctly twice.

The third phase of the experiment involve the critical recognition time procedure. There were 6 blocks of trials and in each block the 56 probes were presented in random order. The screen subtended approximately 23 x 17 degrees of visual angle. The two words were presented in the middle of the screen vertically. One word was 5 degrees left of the center and the other 5 degrees right of center, for a separation of 10 degrees. The words themselves subtended 2-3 degrees of visual angle. This was the only phase of the experiment in which the participant was monitored by the eye-movement equipment. The participant responded to each probe by pressing a key (k for yes or d for no). Then the stimulus was erased and information was presented as to whether the answer was correct or not and the score was displayed at the bottom of the screen. That was displayed for 3 seconds. Then it was erased and the next stimulus was presented. Between blocks the participant was given a chance to take a short break and recalibration was done if necessary.

The eye tracker used to determine participant point-of-regard (POR) during the trials is an ETL-500 manufactured by ISCAN, Inc. The ETL-500 is a high-resolution pupil/corneal reflection dark-pupil tracker that uses a Polhemus FASTRAK magnetic head tracker to compensate for participant head movements during tracking episodes. Under typical operating conditions, the ETL-500 estimates participant POR with an error of less than one degree of visual angle. The tracker was configured with ultra-light head-mounted optics to minimize participant discomfort. Trial event, mouse position, and participant POR data were recorded every 16.7 ms by the experiment delivery software. By interleaving task state information with the participant POR data, the experiment delivery software was able to record trial data files that could be analyzed and replayed after the experiment. If necessary the eye tracker was recalibrated between blocks of the recognition phase.

Design and Analysis. All data were analyzed according to 2x2x3x3 design where the factors are the between-participants factor of order of presentation (person-location or location-person), and the within-participant factors of target versus foil, person fan, and location fan. A number of dependent variables were analyzed in this design. This included the traditional measures of mean percent correct and mean latency for correct judgements but also a number of eye-movement-based measures.

The screen was divided into a left and 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 fixations on the person or location half were aggregated into single fixations reflecting the encoding of one of the terms. In effect, this meant that every time the eye crossed the midpoint of the screen a new fixation was counted and fixation duration was all the time spent on a side of the screen before crossing the boundary. The actual response was counted as terminating the last fixation. Thus, all trials are decomposed into a sequence of one or more alternating fixations starting either with the person or location and ending with a key press. The dependent measures will be order of fixations, number of fixations, and duration of the various fixations.

Results

Table 2 presents the data on latency for correct trials (truncated to a maximum of 5 sec.), error rate, number of fixations, and mean duration of fixations. We also analyzed mean percent first fixations to the left-most element but this showed no significant effects. Participants averaged 83% fixations on the left-first 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 was not enough to significantly impact the difference between the groups (87% versus 78% left-first fixation, $F(1,33) = 2.17$, $p > .10$, $MSE = .573$). None of the other three dependent variables even approached showing a significant effect of group. Therefore, Table 2 collapses the data over this factor. The strong tendency to encode the leftmost element first, combined with a lack of an effect of, what that element was, is inconsistent with a single access-model. Such a model would have the participant retrieve from the first element presented and so its fan should have the dominant impact on retrieval time. That is, such a model predicts, for the measures in Table 2, an interaction both between person fan and order of presentation and between location fan and order of presentation, but both interactions were not significant.

With one exception, there were significant effects of the three within-participant factors on all four dependent measures:

1. 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. Fix num: 3.22 versus 3.37—$F(1,33) = 21.54$, $p < .0001$, $MSE = .167$
    d. Fix time: 431 versus 452 ms—$F(1,33)=29.90$, $p<.0001$,$MSE=2422$

2. 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. Fix num: 3.15, 3.33, 3.41—$F(2,66) = 18.99$, $p < .0001$, $MSE = .190$
    d. Fix time: 432, 439, 453 ms—$F(2,66)=7.68$, $p<.001$,$MSE=3440$

3. 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. Fix num: 3.13, 3.37, 3.39—$F(2,66) = 16.39$, $p < .0001$, $MSE = .267$
   d. Fix time: 428, 444, 452 ms—$F(2,66)=10.27$, $p<.0001$, $MSE=2874$

Note that the total latency is usually a little more than the product of fixation number and fixation time because off-screen fixations are excluded. The discrepancy can be in the opposite direction because the mean latencies were truncated at 5 seconds and we did not apply this truncation to the eye movement data. The effects of location and person fan were approximately identical, replicating past experiments using these material. There were no significant interactions except for the interaction between location and person fan for accuracy ($F(4, 132) = 3.39$; $p < .05$, $MSE = .004$), which in part reflects a min effect (for instance, the 2-2 accuracy is less than the 1-3 or 3-1 accuracy). There was a similar interaction in the latency data in Table 2 but it did not reach significance ($F(4,132) = 1.11$, $p > .1$, $MSE = 46,407$). A specific contrast for the min effect compared the average of 2-2 cell with the average of the 1-3 and 3-1 cells. This difference averaged .018 for accuracy and 102 ms for latency. The test for the accuracy differences was marginally significant ($t_{34} = 1.86$; $p < .05$ one-tailed) and the test for the latency difference was quite significant ($t_{34} = 3.00$; $p < .005$).

<u>Duration of Individual Fixations</u>. As can be seen, the number of fixations averaged a little more than 3 but there was variability. 1.9% of the trials only involved 0 or 1 fixations, 25.0% involved 2, 44.2% involved 3, 15.3% involved 4, 8.2% involved 5, and 5.4% involved more. The analyses to follow exclude those trials where participants make 0 or 1 fixations and all trials where they make errors. In aggregating fixations for purposes of analysis, the first fixation

defines one category but later fixations are open to alternative classifications. There were a little more than 2 subsequent fixations and we will present two different ways of breaking them into two categories. One classification separates them in a second fixation and later fixations (if any). The other classification separates them into a last fixation that terminates when the response was emitted and any intermediate fixations (between first and last).

Figure 1 presents the data classified into first, second, and later fixations. These data are aggregated over the two orders of presentation, which had no significant effects, and the variable of target-versus-foil, which often had significant main effects. There are no significant effects involving first fixation times. The mean latencies for 1, 2, and 3 location fan were 400, 399, and 401 ms and for 1, 2, and 3 person fan 399, 399, and 401 ms. In contrast, there was a significant effect of location fan on second fixation – 473, 474, and 499 ms ($F(2,66) = 5.35$, $p < .01$, $MSE = 5958$). While the effect of person fan was not significant, it was at least in the expected direction – 472, 488, 483 ms ($F(2,66)=1.62$, $MSE = 8030$). The effects of fan appear even larger for the later fixations. The mean times for later fixations in the 1, 2, and 3 location fan conditions were 404, 434, and 450 ms ($F(2,66) = 8.08$, $p < .001$, $MSE = 14162$) and in 1, 2, and 3 person conditions they were 401, 432, and 454 ms ($F(2,66) = 14.99$, $p < .0001$, $MSE = 9962$).

Figure 2 presents a break-out of the data according to first fixation, intermediate fixations, and last fixation. The first fixation data are identical with those that in Figure 1. With respect to intermediate fixations, there were significant effects of both location fan (434, 436, and 457 ms – $F(2,66) = 5.51$, $p < .01$, $MSE = 6371$) and person fan (424, 455, 448 ms – $F(2,66) = 6.76$, $p < .005$, $MSE = 8383$). Similarly, for last fixation time there were significant effects of both location fan (442, 464, and 477 ms – $F(2,66) = 6.71$, $p < .005$, $MSE = 10{,}290$) and person fan (444, 456, 482 ms – $F(2,66) = 9.67$, $p < .001$, $MSE = 8533$).

In summary, Figures 1 and 2 and the accompanying statistics show an effect of fan on duration of all fixations except for the first fixation. Moreover, the sizes of these fan effects are approximately the same for all fixation positions except the first and approximately equal for person and location fan. Nowhere is there any evidence that the fan effect varied with the term being fixated. Figure 1 also presents the predictions of a multiple access model that we will describe later in the paper. This model will also successfully predict the effect of fan on number of fixations. Before presenting that model we will report a second experiment designed to produce asymmetric effects of person and location fan.

Experiment 2

The first experiment found approximately equal effects of person fan and location fan and failed to get any effect of order of presentation on the relative size of the fan effects for person or location. It also failed to find any relationship between eye-movement patterns and the relative fan effects. That is, the size of the fan effects on overall latency did not depend on which item was encoded first and the size of the fan effect on duration of a fixation did not depend on whether it was a person or location term that was being fixated. However, researchers have been able to get differential fan effects on overall latency. For instance, Radvansky, Spieler, and Zacks (1993) found that when people studied sentences asserting inanimate objects were found in locations they only found an effect of object fan. Radvansky et al. attributed their results to participants forming situation models organized around locations. On the other hand, when participants studied facts about people being in small locations, Radvansky et al only found an effect of location fan. This they attributed to participants forming situation models organized around the people. We thought that if we tried to replicate these experiments we would get differential effects of fan and could then explore whether there would be any relationship in these experiments between eye movements and differential fan effects. According to a single-access model, one might conjecture that participants would look differentially at the two terms depending on which term showed the fan effect or that they would only show fan effects for fixation durations on one of the items.

We tried to make our conditions fairly close replications of Experiment 1 (inanimate objects -- large locations) and Experiment 5 (people -- small locations) from Radvansky et al. This meant a number of deviations from the design of our Experiment 1. Perhaps most significantly the phrases denoting the objects, persons, and locations were not always single words but could consist of as many as four words (we used their material). Still we adopted the convention of designating the left side of the screen the object/person region and the right part of the screen the location region. Both of their experiments varied the fan of the terms from 1 to 3 but unlike our Experiment 1, they did not involve complete 3x3 manipulations. Table 3 shows the abstract structure of targets and foils for their two experiments.

Method

Participants. Fifteen participants were in the inanimate object, large location condition and 15 were in the person, small location condition. For simplicity of reference we will refer to these as the object and person conditions. Participants were paid for an experiment that lasted between 1 and 2 hours. The participants were paid a base $15 and no bonus to be consistent with the procedure in Radvansky et al. The experiment lasted approximately 1.5 hours.

Materials. Participants studied 18 sentences whose abstract structure is illustrated in Table 3. The foils were also created as specified in Table 3. In the object condition participants were not tested with the 2-3, 3-2, and 3-3 targets or foils (since Radvansky et al did not test these in their object condition) but these items were used in their person condition. This meant that each block consisted of either 24 or 36 trials. While Radvansky et al used 9 blocks we continued an extra 4 more blocks for a total of 13.

Procedure. The experiment had three phases, all of which were administered on a Macintosh computer. In the first phase of the experiment participants saw the study sentences presented in random order. They were presented in the form "The person is in the location" for 7 seconds each with a .5 second interval between each sentence.

The second phase of the experiment consisted of presenting all of possible questions of the form "Where is the person/object?" and "Who/What is in the location?" until the participant answered them all correctly on 2 successive passes, or 6 times through. The limit of 6 passes was not a part of Radvansky et al's procedure but only 3 participants did not get it right twice in a row before 6 passes.

The third phase of the experiment involve the critical recognition time phase. The stimulus was presented as the full sentence "The person/object is in the place." and was centered on the screen. When the participant pressed a key (k for yes or d for no) the stimulus was erased and if the answer was incorrect a message either "*ERROR* SENTENCE STUDIED" or "*ERROR* SENTENCE NOT STUDIED" was displayed at the bottom of the screen for .5 seconds. If the answer was correct the screen was blank for the .5 seconds before the next presentation. Between blocks the participant was given a chance to take a short break and recalibration was done if necessary. The same eye-tracking equipment was used in this phase of the experiment as in Experiment 1.

Design and Analysis. While we will report the data for all the cells in the design, our statistical analysis will follow the convention of Radvansky et al of just looking at the cases where one of the fans is 1 and look at the effect of the other fan. Thus, the data were analyzed according to 2x2x2x3 design where the factors are the between-participants factor of type of material (inanimate object and large locations versus people and small locations: object-person factor), and the within-participant factors of target versus foil, term whose fan was varied, and value of that fan. The same dependent measures were collected and analyzed in this experiment as in the previous experiment.

Results

Table 4 presents the data on latency, accuracy, number of fixations, and mean duration of fixations, averaging over target versus foil. Participants showed an overwhelming tendency

(97%) to look at the left-most element first and this did not vary with any factor of the experiment. The main effects for other variables were:

1. Condition: object versus person
   a. Error Rate: .025 versus .015, $F(1,28) = 5.29$, $p < .05$, MSE = .0016
   b. Latency: 1461 versus 1729 ms., $F(1,28) = 6.42$, $p < .05$, MSE=1,006,675
   c. Fix num: 3.19 versus 3.32, $F(1,28) = 0.67$, $p > .1$, MSE = 2.50
   d. Fix time: 440 versus 504 ms, $F(1,28)=9.33$, $p<.01$, MSE=39,973

2. Target versus Foil
   a. Error Rate: .020 versus .020—$F(1,28) = 0.03$, $p > .1$, MSE = .0007
   b. Latency: 1536 versus 1653 ms.—$F(1,28) = 35.20$, $p < .0001$, MSE=34,817
   c. Fix num: 3.22 versus 3.30—$F(1,28) = 8.90$, $p < .01$, MSE = .063
   d. Fix time: 461 versus 484 ms.—$F(1,28)=24.41$, $p<.0001$, MSE=1839

3. Fan
   a. Error Rate: .021, .018, .020—$F(2,56) = 0.36$, $p > .1$, MSE = .0009
   b. Latency: 1523, 1606, 1655 ms.—$F(2,56) = 4.87$, $p < .05$, MSE=108,825
   c. Fix num: 3.21, 3.26, 3.30—$F(2,56) = 1.03$, $p > .1$, MSE = .277
   d. Fix time: 460, 475, 482 ms.—$F(2,56)=4.66$, $p<.05$, MSE=4210

4. Dimension: subject versus location
   a. Error Rate: .021 versus .019—$F(1,28)= 1.24$, $p > .1$, MSE = .0005
   b. Latency: 1584 versus 1605 ms.—$F(1,28) = 0.69$, $p > .1$, MSE=55,580
   c. Fix num: 3.27 versus 3.25—$F(1,28) = 0.21$, $p > .1$, MSE = .204
   d. Fix time: 467 versus 477 ms.—$F(1,28)=3.32$, $p<.1$, MSE=2844

The critical interaction is between fan, dimension, and condition such that the fan effect for subject is larger in the object condition but the fan for location is larger in the person condition. This interaction was significant for overall latency ($F(2,56) = 5.13$, $p < .01$, MSE = 46,024) but not for mean latency of a fixation ($F(2,56) = 1.99$, $p > .10$, MSE = 2344) or number of fixations ($F(2,56) = 2.03$, $p < .01$, MSE = .143) although it is in the expected direction for both. Given that this was a replication we felt justified in calculating a number of a priori contrasts. We calculated the differential fan effect as the difference between 3 fan for the subject dimension (location fan = 1) and 3 fan for the location dimension (subject fan = 1). This was 120 ms for the object condition and –233 ms in the person condition. The difference between these two numbers was highly significant ($t(28) = 4.11$, $p < .0005$). The values for number of fixations is .17 versus -.21 which was also significant ($t(28) = 2.15$, $p < .05$). The difference for duration of fixation is 45 ms versus – 5 ms. which was also significant ($t(28) = 2.13$; $p<.05$). Thus, with respect to overall latency we have substantially replicated Radvansky et al showing larger effects of object fan in the object condition and larger effects of location fan in the person condition. The effects appear to be occurring both because of changes in number of fixations and duration of fixations.

<u>Duration of Individual Fixations.</u> Figure 3 shows the effect as a function of the two fans for first fixation, second fixation, and later fixations averaged over group. These data were collapsed into major dimension (subject fan for object experiment and location fan for person experiment) and minor dimension (location fan for object experiment and subject fan for person experiment). The major dimension should show the larger effect of fan. We calculated statistical contrasts to test for an effect of fan (fan 3 – fan 1) and for differential fan 3 latencies for the major and minor dimensions. This latter contrast is the difference between fan 3 for major and minor dimensions. With respect to first fixation, neither contrast was significant – neither the fan effect (4 ms.—$t(29) = .53$) nor the difference between fan 3 conditions (-17 ms.—$t(28) = .67$) With respect to second fixations there was a significant effect of fan (19 ms.—$t(29) = 2.09$, $p < .05$) and a marginally significant differential fan 3 effect (51 ms.—$t(28) = 1.58$, $p < .10$). For the third fixation both effects were quite large and significant -- the effect of fan (42 ms.—$t(29) = 3.77$, $p < .001$) and the differential fan 3 effect (77 ms.— $t(28) = 2.57$, $p < .05$).

Figure 4 shows a break-down of the data according to first, intermediate, and last fixations. With respect to intermediate fixations there was a significant effect of fan (25 ms.—$t(29) = 2.48$, $p < .01$) and a significant differential fan effect (73 ms.—$t(28) = 2.80$, $p < .005$). Similarly, for last fixations there was a significant effect of fan (38 ms.—$t(29) = 3.28$, $p < .005$) and a non-significant differential fan effect in the expected direction (37 ms.— $(28) = 1.18$).

So, in summary, while this experiment found a differential fan effect, it found little evidence that this is related to fixation position except that no effects are seen for the first fixation. While one might view the differential fan effect as evidence for a single-access model, neither Radvansky nor Anderson and Reder (1999a) view it this way in their alternative models. Radvansky's theory roughly holds that participants access the situation with both terms but only the fan on the non-situation term can cause the situations to be similar slowing down retrieval. Anderson and Reder (1999a) and the model we will present assumes that participants differentially weight person and location according to the nature of the material. What would be critical as evidence for the single-access model is some evidence that this differential fan effect was related to the pattern of fixations and again there was no such evidence. While the data are inconsistent with a the single-access model the issue remains of how a multiple-access model can account in detail for this pattern of data. The next section presents two such models.

Models[3]

The natural assumption was that fan effects for a particular fixation reflected some process happening and competing during that fixation which is affected by fan. However, upon careful reflection we realized that this need not be the case and indeed there was a better way to provide a precise account for the data. This was that there was a race going on between a process that generated eye movements, which was determined by factors unrelated to fan, and a retrieval process, which was affected by fan. Once the items had been encoded we assume that the eyes just moved back and forth occasionally for reasons unrelated to retrieval. However, there should an effect of fan because the participant could complete retrieval and respond before the next eye movement. This process served to truncate long-duration fixations in the low-fan conditions and yield shorter mean fixation durations.

We will present two models that partially formalized this understanding of what was happening in these experiments. The first model was developed to predict mean effects of fan on number of fixations and duration of fixations. The second model involves an elaboration to account for the distribution of fixation times but at the cost of analytic tractability so that we are no longer able to predict mean times.

Exponential Model

According to the first model there were three times describing eye movements – mean time E1 to encode the first term, mean time E2 to encode the second term, and mean time E3 before moving the eyes during retrieval. This last encoding time was the one that raced with a retrieval+response process with mean time R. If we assume, for purposes of analytic tractability, that these times are distributed as exponentials, then the mean time for a fixation (whether it ends with an eye movement or response) is

Retrieval-Duration = E3*R/(E3+R).

The mean number of fixations during the retrieval phase is

Retrieval-Number = (E3 + R)/E3

Note, that this implies that, even though eye fixations are not involved in retrieval their duration and number will show fan efforts because of the race between completion of retrieval and execution of the next eye movement. If the retrieval time is long in a high-fan condition this will be an opportunity for long fixations whereas such fixations would be truncated by fast retrievals in a low-fan condition. Under this analysis, the dependent variables become:

Duration of first fixation = E1

Duration of second fixation = E2 + Retrieval-Duration

Duration of later fixations = Retrieval-Duration

Number of Fixations = 1 + Retrieval-Number

The data can be predicted by estimating E1, E2, E3, and R. To estimate the retrieval times, R, we used the same models of the fan effect as in Anderson and Reder (1999a). That model predicts that retrieval time R for sentence i is calculated

$$\mathrm{R} = D + Fe^{-A_i}$$

where D is the decision time, F is the latency scale, and A_i is the activation of the memory trace for sentence i. The activation A_i is calculated as

$$A_i = \sum W_j S_{ji}$$

where the summation is over the terms j in the probe, W_j is the weighting given to the jth element, and S_{ji} is the strength of association from j to i. In line with Reder and Anderson, we assume that there are sources j corresponding to person, location, and the relation in. S_{ji} is calculated as

$$S_{ji} = S - \ln(fan_j)$$

where S is a parameter to be estimated and fan_j is the fan from the jth element. Also, in accord with Anderson and Reder, assume that the W_j are all 1/3 in Exp 1 but that the person and location W_j are divided unevenly in Exp. 2. Thus, an additional parameter is the proportion, W*, of attention given to the major dimension in Exp 2 (where 2/3 - W* is the weighting given to the minor dimension).

Given that the material was different between the two experiments we estimated separate values of the three encoding parameters (E1, E2, and E3) for the two experiments but constrained the memory and response parameters (S, F, & D) to be the same. With the attention parameter, W*, for Experiment 2 this gives 10 parameters. With these parameters we can predict the mean number of fixations and mean fixation times. For mean fixation times, we focused on the division into first, second, and later fixations since this was the partitioning that was significant according to the model. The predictions of the model for fixation time are illustrated in Figures 1 & 3 and for number of fixations in Figure 5. The fits are collapsed over the dimension of target versus foil and focus on predicting fan effect. There are 9 conditions in Experiment 1 and 5 conditions in Experiment 2. With 4 dependent measures there are (9+5) x 4 = 56 predictions altogether. With 10 parameters there are 56-10 = 46 degrees of freedom. The following value is thus distributed as a chi-square with 46 degrees of freedom:

$$\chi^2(46) = \sum_{conditions} \left(\hat{Y} - \overline{Y}\right)^2 \Big/ s_{\overline{Y}}^2$$

where the summation is over the 54 conditions and the quantity summed is square of the difference between the prediction and the mean for that condition divided by the variance for that dependent variable. The chi square measure was 52.33 which is not significant suggesting a good fit. The encoding and eye movements parameters estimated were E1 = 400 ms, E2 = 54 ms, and E3 = 759 ms for Experiment 1 and E1 = 534 ms, E2 = 63 ms, and E3 = 718 ms for Experiment 2. The values for the two experiments are similar. E1 and E2 are probably somewhat longer for Experiment 2 reflecting the lexically longer terms. The additional material on the screen might also have encouraged participants to look back and forth more often resulting in the slightly lower value of E3 in Experiment 2. E2 is strikingly low compared to the other two encoding parameters (E1 and E3), but unlike the other two, but it does not reflect a complete fixation (which would include programming the next saccade)—just sufficient encoding to initiate retrieval. The other parameters were S = 1.10, F = 806 ms, D = 344 ms, and W* = .50. The values of S, F, and W* are similar to values estimated in Anderson and Reder (average values S = 1.36, F = 878 ms, W* = .54 in that paper). That paper did not obtain an independent estimate of D but rather an estimate that aggregated encoding and D. The value of this aggregate "intercept" parameter (847 ms. for the classic fan paradigm in Anderson and Reder) is close to the average sum of the encoding (E1 and E2) and response (D) parameters in the first experiment (798 ms). Moreover, the estimate of D is reasonable as decision time plus response generation. This model illustrates how a multiple-access model with a race between eye movements and retrieval process can give rise to the pattern of fan effects in both number of fixations and mean duration per fixation.

Lognormal Model

For purposes of analytic tractability the preceding model made the assumption that the times were exponential. The assumption of exponential distribution of times in the preceding model, while mathematically convenient, is clearly unrealistic. Figure 6 shows the actual distribution of latencies in Experiment 1. It collapses the conditions from that experiment 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). Plotted separately are the distributions of latencies for (a) first fixations, (b) second fixations that do not end with a response, (c) second fixations that do, (d) third fixations that do not end with a response, and (e) third fixations that do. Beyond three fixations, the number of observations rapidly decreases. The data are smoothed by taking the average of 9 points (i.e. point n is the average of the raw values for fixations n-4 to n+4). Also plotted are the predictions of a model that assumes the actual latencies are lognormal in distribution.

With respect to first fixation, we see that not only is the mean unaffected by fan but the full distribution is identical in all fan conditions. This is strong evidence that participants do not begin retrieval on the first fixation. All the other fixations in Figure 6 show some effect of fan, but the effect is much larger on those fixations that end with a response. The model fitted to the first fixation data assumed a lognormal distribution with mean 414 msec and standard deviation 108 milliseconds. Figure 6a shows that a lognormal gives a remarkably good fit except for a mass of unpredicted short fixations which probably reflect spurious first fixations before the true first encoding fixation.

For later fixations we assumed, as in the preceding model, a race between two distributions, a Saccade distribution for moving the eye and a Response distribution for completing the retrieval and generating the response. However, we now modeled these distributions as lognormals. There are not simple equations for the winners of races between such distributions and the calculations become particularly complex when we look at the distributions for the third fixations, which are conditional on the second fixation completing before recall.

In all fan conditions a single lognormal distribution was assumed for the Saccade distribution. This distribution had a mean of 483 msec and a standard deviation of 274 msec. Three Response distributions were estimated for the three fan conditions. They were constrained to have means equal to the mean time in these conditions after the first fixation – 977 msec for low fan, 1074 msec for medium fan, and 1215 msec in the high fan condition. The standard deviations were, on the other hand, estimated and these were 461 msec in the low fan condition, 517 msec in the medium fan condition, and 586 in the high fan condition. As parts (b) – (e) of the Figure 6 illustrate, this model does a relatively good job of capturing the qualitative character of the distributions although quantitatively it is a good bit off in places. Given that these are data averaged over participants, conditions, and degrees of practice it is not realistic to expect that the model would yield exact fits to the distributions resulting from a race process. (The model assumes independence of the Response and Saccade distributions but such averaging produces serious dependencies.) Nonetheless, this does serve to show how the actual latencies could arise from a race process. Particularly compelling here is the distribution in Figure 6e for third fixations that end in a response. This is an unusual latency distribution, which results from the saccade between second and third fixation interrupting the Response distribution. To an approximation we are seeing the slower tail of the Response distribution with the faster responses having resulted in a response before the saccade in Figure 6c (although the predictions in the figure are conditionally calculated and not so simple).

So, in conclusion, there are two key features to our understanding of the data. The first is the multiple-access assumption, which implies no effect of fan on first fixation. The second is the idea that later fixation durations are determined by a race between a retrieval process determined by fan and an eye movement process which is not affected by fan. The two models are both partial illustrations of this understanding of the data. The first, based on the exponential distribution, is analytically tractable and fits all the data on mean number of latencies and number of fixations. The second, based on the lognormal distribution, fits only the first, second, and third fixations. However, it does better capture the qualitative character of the latency distributions.

Conclusions

These experiments provide two pieces of evidence for the multiple-access assumption – the fact that effects of fan appeared only after both terms were fixated and the fact that there was no relationship between the relative size of fan effects and which terms were fixated. Anderson and Reder (1999b) note that there has been a failure to find a consistent effect of fan of pre-cueing with a term in an effort to influence which item a participant chooses to retrieve from. The failure to get pre-cueing effects on fan also indicates that participants must wait to encode both terms before initiating a retrieval.

It is possible to still salvage a single-access model in the presence of the data from the current experiments. One could propose that participants choose not to retrieve until both concepts are encoded but then retrieve only from a randomly chosen single item. This assumption, combined with a model of eye movements like that described, would be consistent with the major trends in the data. It is not clear, however, why retrieval would be delayed until the second term is encoded if retrieval can be initiated from a single term.

The data are consistent with the view that the only function of eye movements in this experiment is to encode the memory cues. While fixations after the first show an effect of fan movements this is consistent with a model that assumes a race between a retrieval process, which is affected by fan, and an asynchronous process that requests eye movements, which is not. These fixations show an effect of fan because, in the race between fixation and retrieval, long fixations are more likely to be truncated by a response in low-fan conditions.

The model paints a rather striking picture of cognition between the period after which the stimulus has been encoded and before the decision and response processes begin. The retrieval process is averaging in the vicinity of a second. During the interval, the "mind" is in something of a state of suspended processing waiting for retrieval to complete. During this time there are occasional eye movements, perhaps initiated by some external data-driven cue. However, short of this the system is suspended waiting for critical information to come in. This is exactly the characterization of cognition according to the ACT-R architecture (Anderson & Lebiere, 1998) where productions rules wait for critical changes in state to occur, quickly react, and wait again. In ACT-R models for many tasks the majority of the time is spent by the production system waiting for the next critical event which is often a retrieval.

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Footnotes/Endnotes

1 This research was supported by National Science Foundation Grant BCS 997-5-220. We would like to thank Craig Haimson for his comments on this article.

2 Wolford (1971) proposed one of the early models of single-cue access for recognition of multiple-cue probes, but in this case for paired-associate accuracy.

3 Both models are available on the Web from the Published Models Link at the ACT-R home page act.psy.cmu.edu or act-r.com.

Table 1

Design of Experiment 1:
Letters (a-q) denote people and numbers (1-17) denote locations

(a) Targets

		Person Fan		
		1	**2**	**3**
	1	a-1	d-4	g-7
		b-2	e-5	h-8
		c-3	f-6	i-9
Location Fan	**2**	j-10	e-10	g-17
		k-11	p-17	h-16
		l-12	d-11	i-12
			q-16	
	3	m-13	q-13	g-13
		n-14	p-14	h-14
		o-15	f-15	i-15

(b) Foils There are two possible locations for each person

		Person Fan		
		1	**2**	**3**
	1	a-3/2	d-6/5	g-9/8
		b-1/3	e-4/6	h-7/9
		c-2/1	f-5/4	i-8/7
Location Fan	**2**	j-12/11	e-11/17	g-12/16
		k-10/12	p-16/11	h-17/12
		l-11/10	d-10/16	i-16/17
			q-17/10	
	3	m-15/14	q-15/14	g-15/14
		n-13/15	p-13/15	h-13/15
		o-14/13	f-14/13	i-14/13

Table 2

Results of Experiment 1:
Mean latency, error rate, number of fixations, and fixation duration

(a) Targets

		Person Fan			
		1	**2**	**3**	Average
	1	1264 ms	1399 ms	1364 ms	1342 ms
		.038	.037	.048	.041
		2.95	3.15	3.13	3.08
		420 ms	435 ms	424 ms	426 ms
Location Fan	**2**	1325 ms	1463 ms	1549 ms	1446 ms
		.040	.062	.098	.067
		3.09	3.32	3.40	3.27
		417 ms	423 ms	444 ms	428 ms
	3	1385 ms	1538 ms	1571 ms	1498 ms
		.037	.086	.079	.067
		3.18	3.42	3.37	3.32
		417 ms	439 ms	456 ms	437 ms
Average		1324 ms	1467 ms	1495 ms	1429 ms
		.038	.061	.075	.058
		3.07	3.29	3.30	3.22
		418 ms	432 ms	441 ms	431 ms

Table 2 Continued

(b) Foils		**Person Fan**			
		1	**2**	**3**	Average
	1	1354 ms .048 3.09 422 ms	1532 ms .041 3.31 442 ms	1514 ms .054 3.28 447 ms	1466 ms .048 3.23 437 ms
Location Fan	**2**	1451 ms .040 3.21 443 ms	1650 ms .069 3.51 455 ms	1609 ms .068 3.45 449 ms	1570 ms .059 3.39 449 ms
	3	1556 ms .052 3.27 452 ms	1701 ms .094 3.50 465 ms	1806 ms .124 3.73 491 ms	1688 ms .090 3.50 469 ms
Average		1454 ms .047 3.19 439 ms	1627 ms .068 3.44 454 ms	1643 ms .082 3.49 462 ms	1575 ms .066 3.37 452 ms

Table 3

Design of Experiment 2
Letters (a-l) denote subjects (people or objects) and numbers (1-12) denote locations

(a) Targets

		Person Fan 1	Person Fan 2	Person Fan 3
		a-1	i-9	k-11
	1	b-2	j-10	l-12
		c-3		
		d-4		
		e-5		k-5
Location Fan	**2**	f-6		l-6
		g-7	i-7	k-7
	3	h-8	j-8	l-8

(b) Foils

		Person Fan 1	Person Fan 2	Person Fan 3
		a-2	i-10	k-12
	1	b-1	j-9	l-11
		c-4		
		d-3		
		e-6		k-6
Location Fan	**2**	f-5		l-5
		g-8	i-8	k-8
	3	h-7	j-7	l-7

Table 4

Results of Experiment 2:
Mean latency, error rate, number of fixations, and fixation duration.

(a) Object-Large Location

		Object Fan		
		1	**2**	**3**
	1	1390 ms .029 3.12 434 ms	1541 ms .033 3.32 440 ms	1561 ms .022 3.33 481 ms
Location Fan	**2**	1441 ms .015 3.14 436 ms		
	3	1441 ms .019 3.11 445 ms		

(b) Person-Small Location

		Person Fan		
		1	**2**	**3**
	1	1656 ms .013 3.30 485 ms	1666 ms .014 3.24 500 ms	1692 ms .015 3.31 494 ms
Location Fan	**2**	1776 ms .010 3.34 525 ms		1894 ms .029 3.46 531 ms
	3	1925 ms .025 3.47 538 ms	2067 ms .025 3.78 514 ms	2009 ms .018 3.78 520 ms

Figure Captions

Figure 1 Fixation durations in Experiment 1. Later fixations are divided into second and rest. Solid lines reflect predictions of model.

Figure 2 Fixation durations in Experiment 1. Fixations after the first are divided into intermediate and last.

Figure 3 Fixation durations in Experiment 2. Later fixations are divided into second and rest. Solid lines reflect predictions of model.

Figure 4 Fixation durations in Experiment 2. Fixations after the first are divided into intermediate and last.

Figure 5 Predictions of the model for number of fixations: (a) Experiment 1 and (b) Experiment 2.

Figure 6 Probability densities of a fixation terminating by each 1/60 of a second (when eye position is recorded). If n is the number of observations for the ith time sample and N is the total number of fixations, probability density is calculated as 60n/N. These numbers are smoothed averages based on the value for that time plus up to 4 earlier and later time samples. Part (a) for first fixation is based on about 3,500 observations for each fan (low, medium, high); part (b) for second fixations that do not end in responses is based on about 2,500; part (c) for second fixations that end with a response on about 1,000 observations; part (d) for third fixations that end with a response on approximately 1,000 observations; and part (e) for third fixations that end with a response on approximately 1,500 observations.

Figure 1

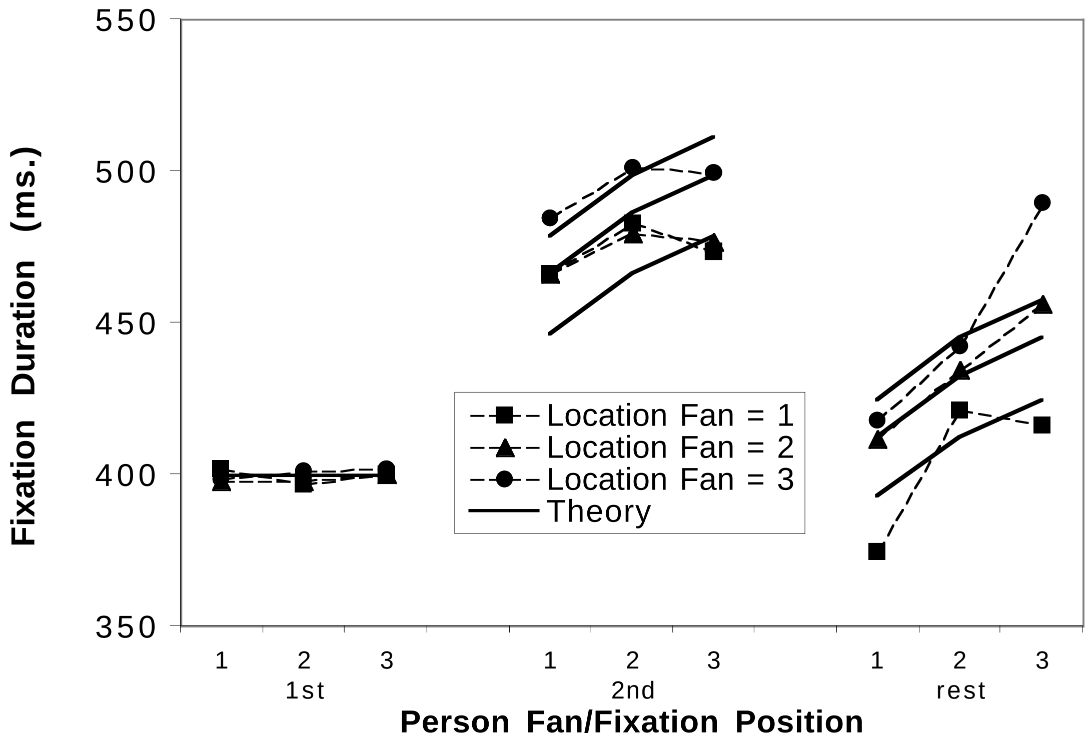

550
500
450
400
350
Fixation Duration (ms.)
Location Fan = 1
Location Fan = 2
Location Fan = 3
Theory
1
2
3
1st
1
2
3
2nd
1
2
3
rest
Person Fan/Fixation Position

Figure 2

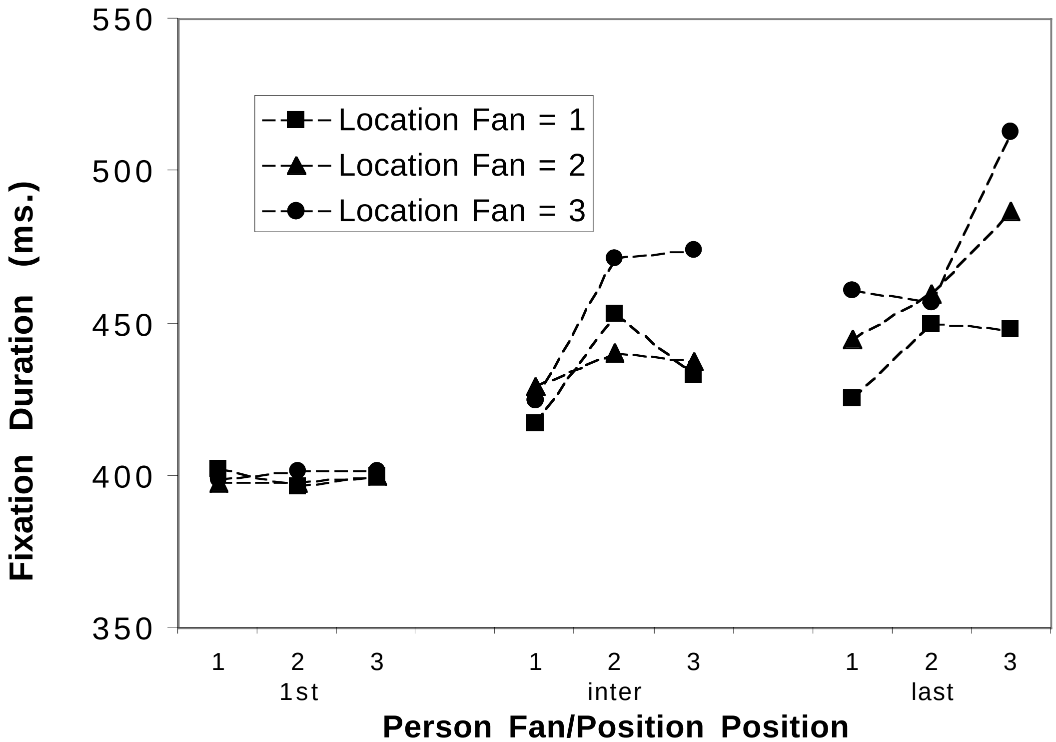

550
500
450
400
350
Fixation Duration (ms.)
Location Fan = 1
Location Fan = 2
Location Fan = 3
1 2 3
1st
1 2 3
inter
1 2 3
last
Person Fan/Position Position

Figure 3

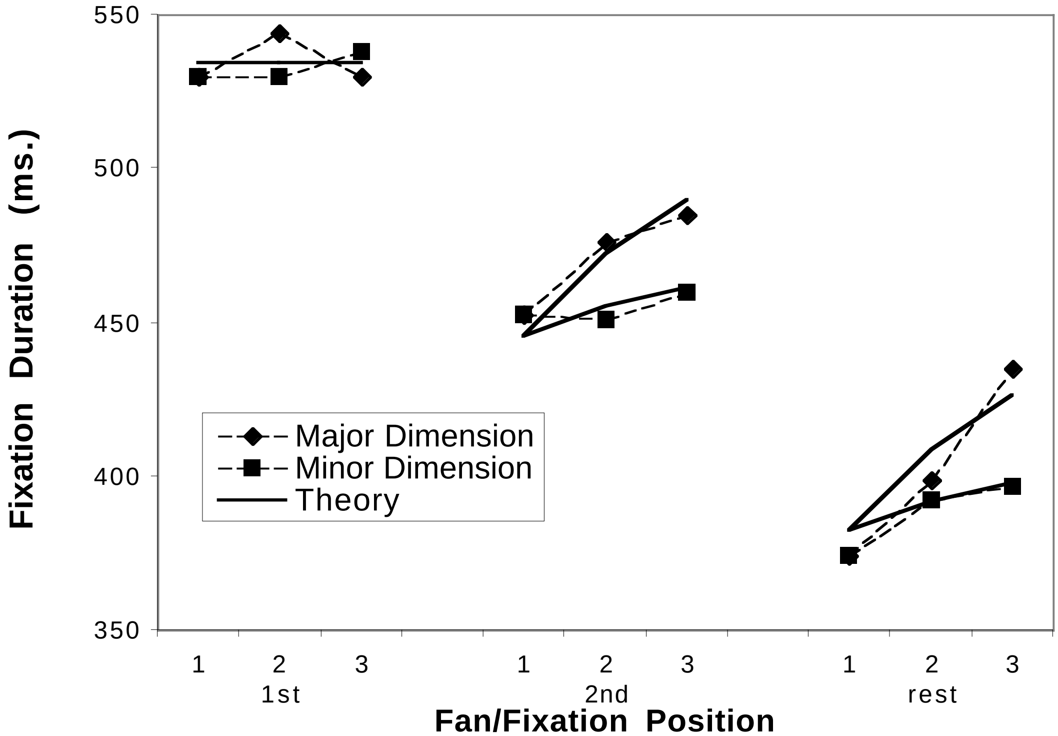

550
500
450
400
350
Fixation Duration (ms.)
Major Dimension
Minor Dimension
Theory
1 2 3
1st
1 2 3
2nd
1 2 3
rest
Fan/Fixation Position

Figure 4

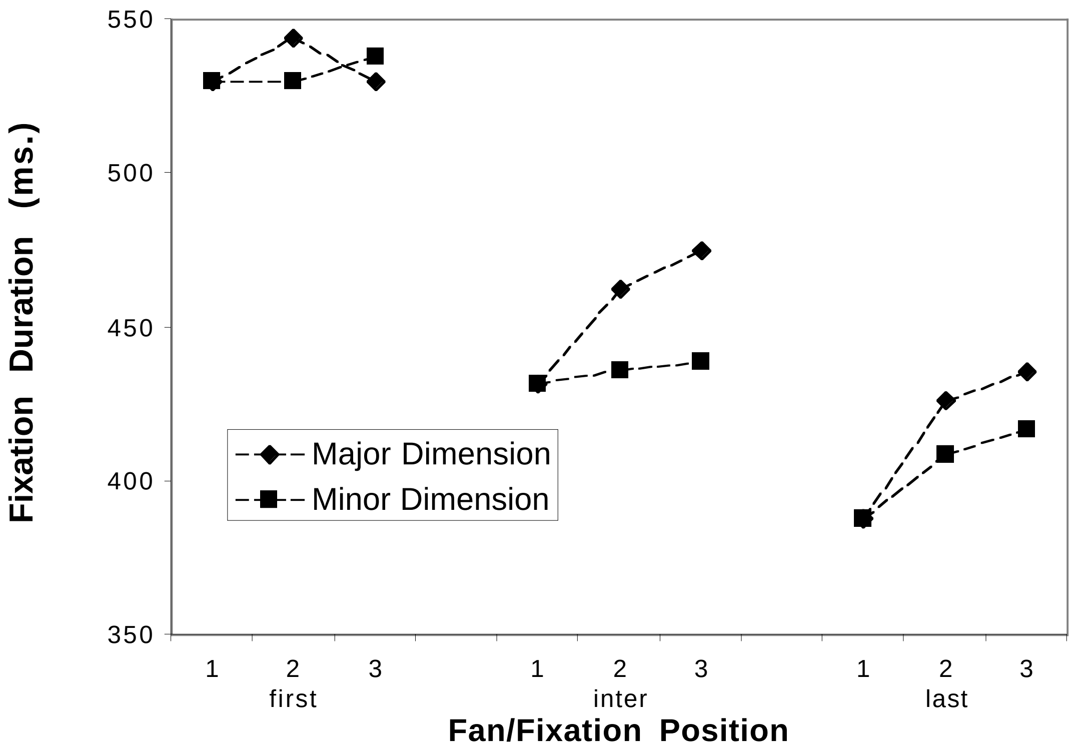

550
500
450
400
350
Fixation Duration (ms.)
Major Dimension
Minor Dimension
1
2
3
first
1
2
3
inter
1
2
3
last
Fan/Fixation Position

Figure 5a

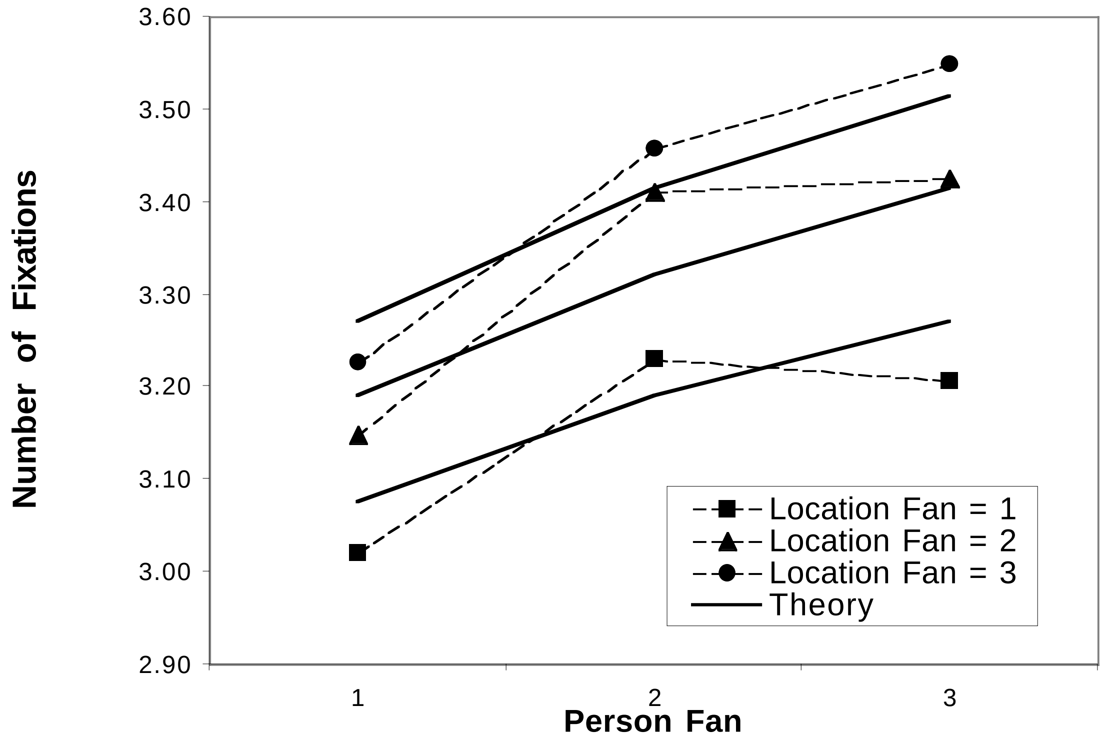


Figure 5b

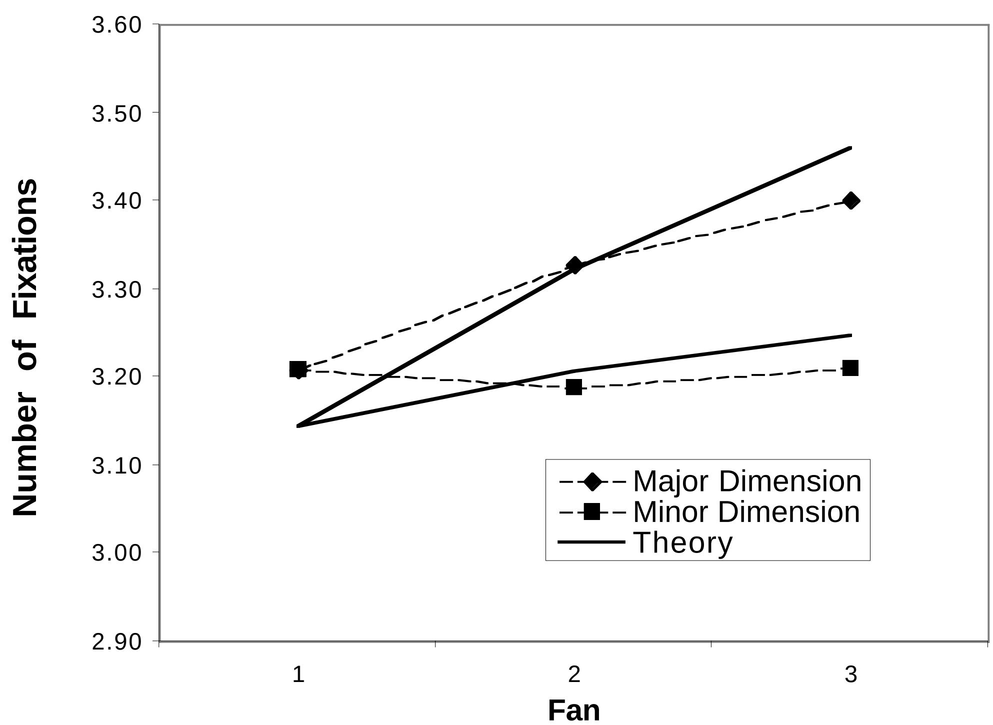
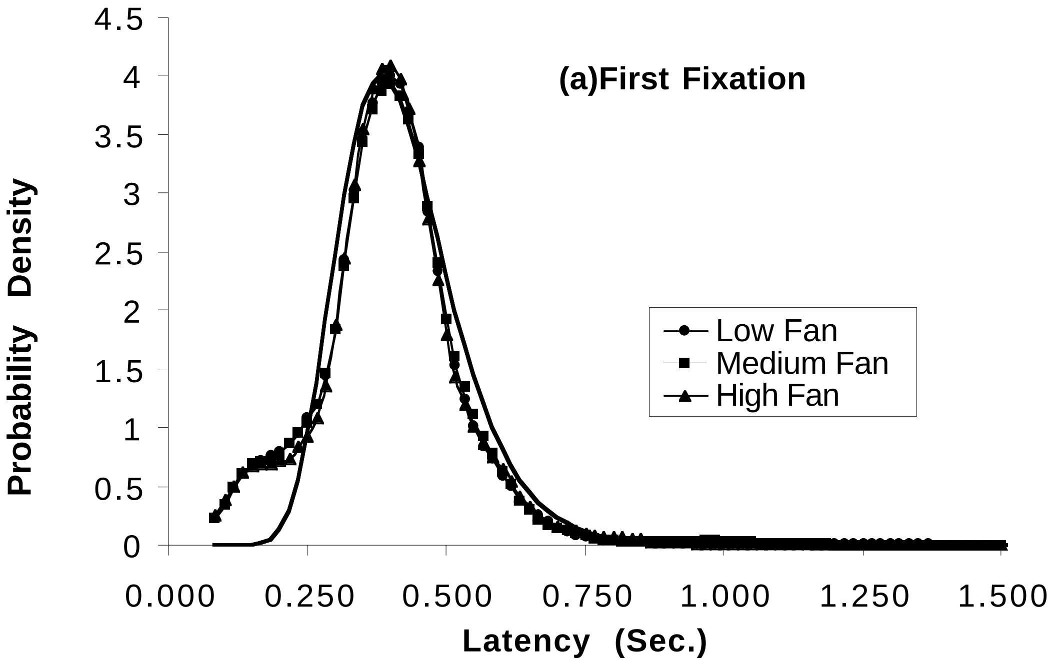
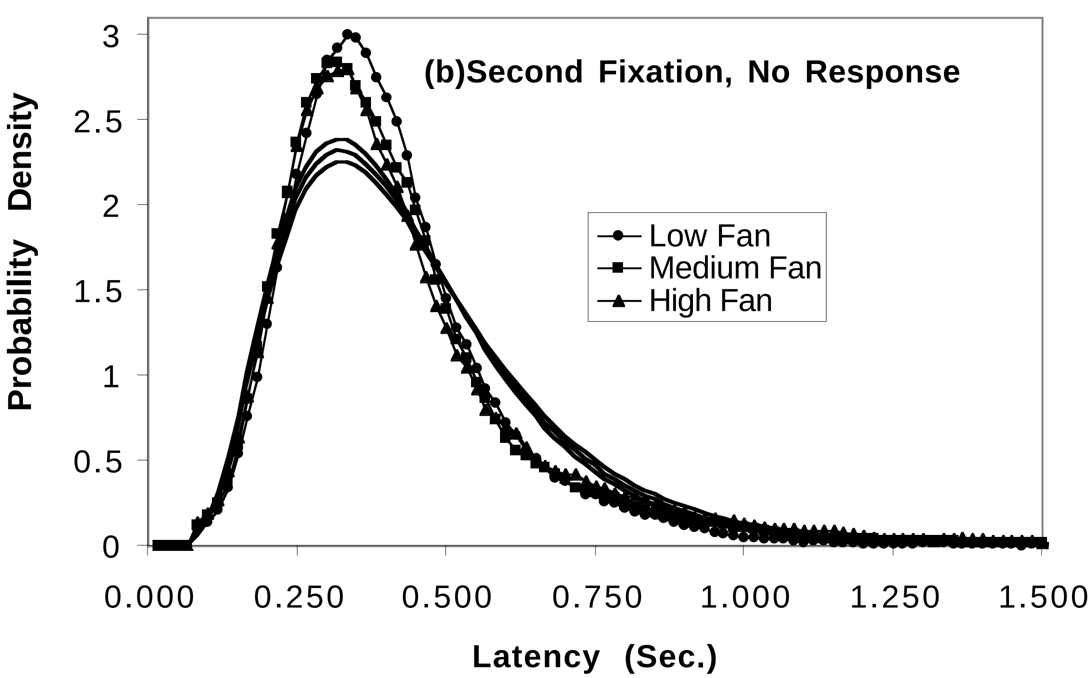
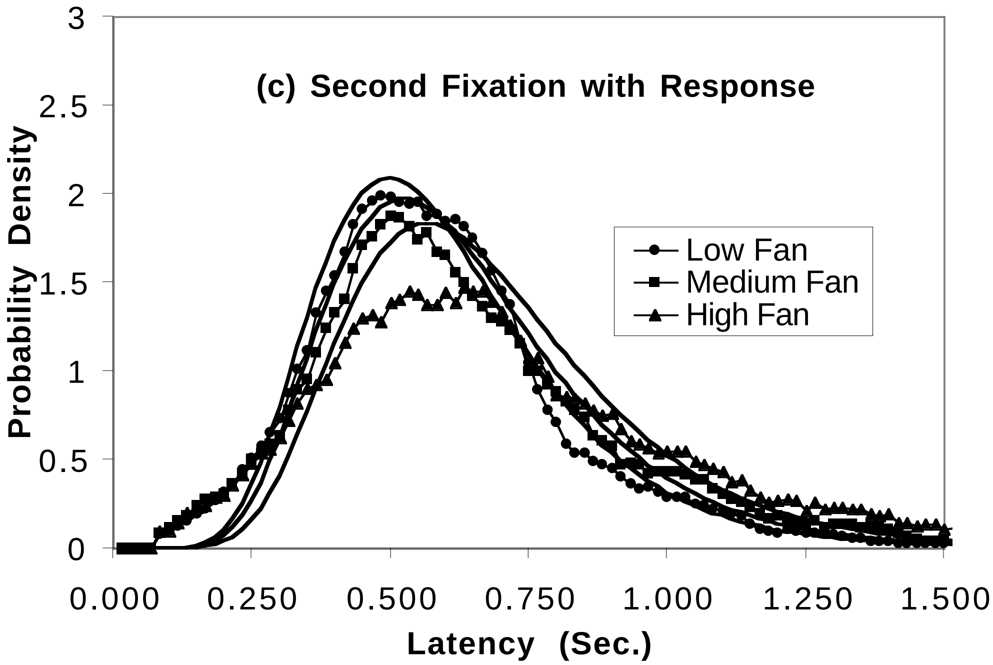
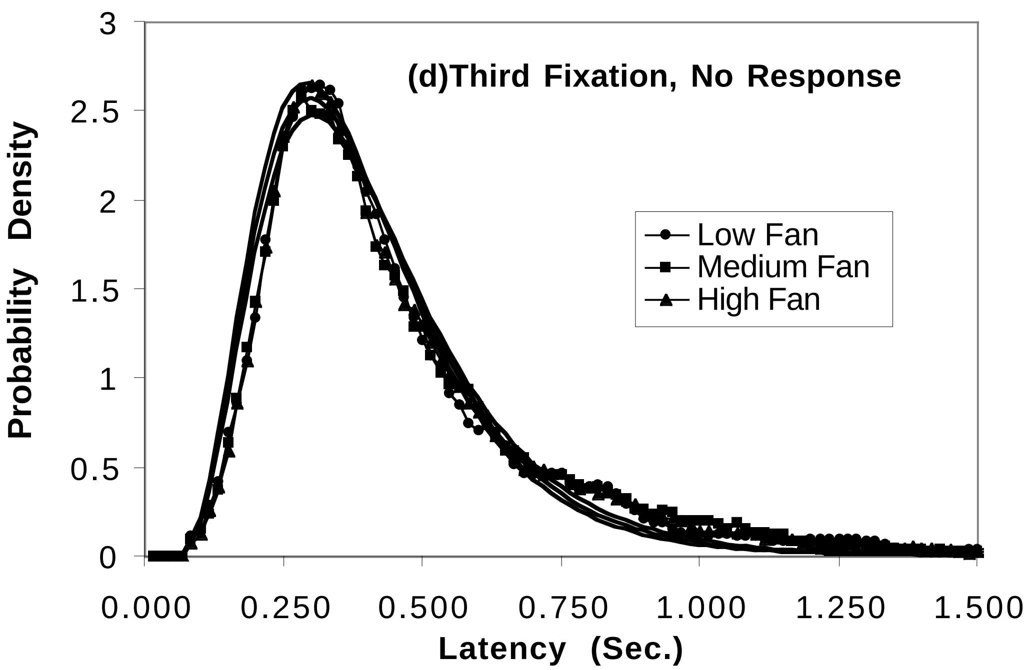


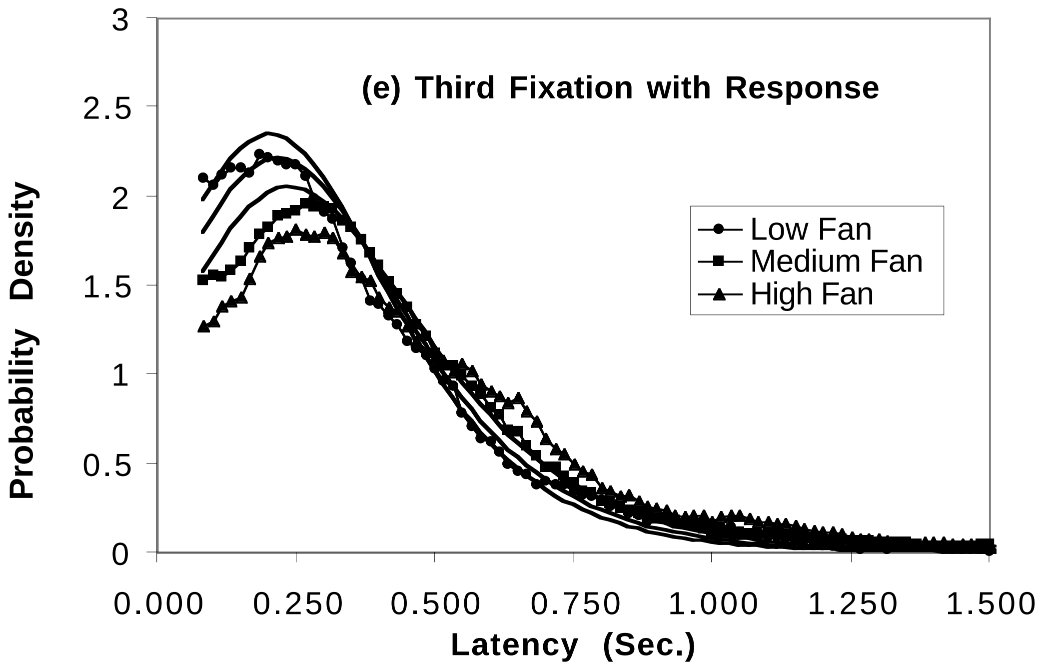
Figure 6


(a)First Fixation
Probability Density
Latency (Sec.)
Low Fan
Medium Fan
High Fan
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.000
0.250
0.500
0.750
1.000
1.250
1.500


(b)Second Fixation, No Response
Probability Density
Latency (Sec.)
Low Fan
Medium Fan
High Fan
3
2.5
2
1.5
1
0.5
0
0.000
0.250
0.500
0.750
1.000
1.250
1.500


(c) Second Fixation with Response
Probability Density
3
2.5
2
1.5
1
0.5
0
0.000
0.250
0.500
0.750
1.000
1.250
1.500
Latency (Sec.)
Low Fan
Medium Fan
High Fan


(d)Third Fixation, No Response
Probability Density
3
2.5
2
1.5
1
0.5
0
0.000
0.250
0.500
0.750
1.000
1.250
1.500
Latency (Sec.)
Low Fan
Medium Fan
High Fan



Probability Density

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[2] Wolford (1971) proposed one of the early models of single-cue access for recognition of multiple-cue probes, but in this case for paired associate accuracy.

[3] Both models are available on the Web from the Published Models Link at the ACT-R home page act.psy.cmu.edu or act-r.com.