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The Emergence of Frequency Effects in Eye Movements

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Abstract

A visual search experiment employed strings of Landolt *C*s to examine how the gap size of and frequency of exposure to distractor strings affected eye movements. Increases in gap size were associated with shorter first-fixation durations, gaze durations, and total times, as well as fewer fixations. Importantly, both the number and duration of fixations decreased with repeated exposures. The findings provide evidence for the role of cognition in guiding eye-movements, and a potential explanation for *word-frequency effects* observed in reading.

Keywords

eye-movement control; word frequency effects; reading; visual search

The extent to which oculomotor and cognitive factors influence eye movements in reading is widely debated (Starr & Rayner, 2001). *Oculomotor* theories contend that the timing and location of fixations are predominantly determined by visual acuity and oculomotor constraints (e.g., McDonald, Carpenter & Shillcock, 2005; O'Regan, 1990; Yang & McConkie, 2001). *Cognitive* (*processing*) theories (e.g., Just & Carpenter, 1980; Reichle, Pollatsek, Fischer, & Rayner, 1998; Reilly & Radach, 2006) argue that cognitive processes like word identification largely drive eye movements, as evidenced by *word-frequency effects*, or the finding that higher frequency words receive shorter fixations and are skipped more often than lower frequency words (e.g., Inhoff & Rayner, 1986).

To determine cognition's involvement in eye-movement guidance during reading, eye movements during reading have been compared to eye movements during tasks presumed to minimally engage cognition, such as searching for a target word in a text or performing z-string "reading" (Rayner & Fischer, 1996; Rayner & Raney, 1996; Vitu, O'Regan, Inhoff & Topolski, 1995). In these tasks, the word-frequency effects that are ubiquitous in reading are absent. Assuming that word-frequency effects arise because more exposures make a word's representation in memory easier to access, as posited by several episodic models of printed word identification (e.g., Ans, Carbonnel, & Valdois, 1998; Reichle & Perfetti, 2003), this may be evidence that eye movements are guided by the demands of accessing lexical representations from memory during reading, but not during tasks that don't require full lexical retrieval.

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The current experiment investigates how manipulating the frequency of orthographic patterns in a visual-search task affects eye movements. Demonstrating frequency effects in a non-reading task would provide strong evidence that cognition rapidly influences eye movements and address the etiology of word-frequency effects in reading. Because associations between word frequency and fixation durations are inherently correlational, some have argued that the causal nature of this relationship remains conjectural (cf., Kliegl, Nuthmann, & Engbert, 2006; Rayner, Pollatsek, Drieghe, Slattery & Reichle, 2007). The current experiment directly tests the hypothesis that frequency effects arise from frequency of exposure by manipulating the latter to determine *if* and *how* eye-movement measures are affected.

We used a paradigm from Williams and Pollatsek (2007; see also Corbic, Glober, & Radach, 2007), in which participants scanned lines of *Landolt-C* clusters, or circles with a missing segment of varying size and orientation, to locate clusters containing an *O*, i.e., targets. In Williams and Pollatsek (2007), the number of pixels in the missing segments, or *gap size*, was held constant within a given cluster, but manipulated between clusters. Their results indicated that fixation durations on the non-target or *distractor* clusters were related to the gap size of the fixated cluster, but not to the gap sizes of neighboring clusters. Furthermore, gaze durations on clusters during scanning were nearly equivalent to reaction times for target present-absent judgments on the same clusters in isolation. Because these results parallel the finding that gaze durations on words in reading correlate with the identification times of those same words displayed in isolation (Schilling, Rayner & Chumbley, 1998), Williams and Pollatsek argued that eye movements in their task were also driven by identification processes, and thus cognition. However, given that gap-size manipulations directly affect *C-O* discriminability, gap-size effects are likely to be influenced by perceptual fluency. Even more compelling evidence for cognitive effects would be provided by a demonstration that the accessibility of individual clusters' memory representations affects eye movements.

Our study extends Williams and Pollatsek (2007) by manipulating the number of times a cluster appeared in the experiment. We predict an inverse relationship between the number of encounters and fixation durations on the distractor clusters. This finding would suggest that the accessibility of a cluster's representation in memory (as determined by frequency of exposure) influences how long that cluster must be processed and thus how long the eyes stay on it. This would provide stronger evidence of cognition influencing eye movements and would exemplify how the mind-eye link may develop in tasks like reading.

Method

Participants

Sixteen University of Pittsburgh undergraduates with normal or corrected vision received partial course credit in an introductory psychology course for their participation.

Procedure

Each trial began with participants viewing a dot on the leftmost side of the screen. Participants initiated the trial with a button press, which displayed the stimuli for 12 seconds. Participants were instructed to scan a horizontal row of clusters from left to right and to identify any targets, i.e., a cluster containing a letter *O* (see Fig. 1). When their gaze shifted to the right of the line, the stimuli disappeared and were replaced by a question mark. Participants pressed joystick buttons to make a target present/absent response. Performance feedback was provided for all trials.

Experimental Design and Materials

Participants completed four blocks of 29 trials. The order of blocks was counterbalanced across participants. In each block, eight trials contained a single target. Targets appeared with equal probability in any cluster position. Clusters were 4-characters long with gap sizes of 2-, 4-, 6-, and 8-pixels. Gap size was constant within a cluster but gap orientation (left, right, top, or bottom) was randomized to create eight unique exemplars for each of the three frequency categories: 10, 25, or 50 encounters. All other clusters occurred only once, resulting in total of 896 distractors. The assignment of distractors to trials was randomized, with each block containing two tokens of each frequency category and 54 unique clusters. This allowed frequency of exposure to be dissociated from practice.

Equipment

Participants viewed the stimuli binocularly on a 23-in. monitor 63 cm from their eyes with approximately 3.5 letters per degree of visual angle. An EyeLink 1000 eye-tracker (SR Research Ltd.) recorded the gaze location of the right eye. The eye-tracker had a spatial resolution of 0.01° and sampled gaze location every millisecond. Task presentation was done using E-Builder software (SR Research Ltd.).

Results

Behavioral Results

Participants' mean accuracy on the search task was greater than 90%. The average hit rate was 87%, the false alarm rate less than 1.5%, and there was only one failure to respond within 12 seconds.

Eye-Movement Results

Analyses focus exclusively on distractor clusters because only distractor frequency was manipulated. The following eye-movement measures were examined on a given cluster: (a) *first-fixation duration*, or the duration of the initial fixation during first-pass scanning; (b) *gaze duration*, or the sum of all first-pass fixation durations; (c) *total-viewing time*, or the sum of all fixations; (d) *number of fixations* during the first pass; (e) *spill-over*, or the first-fixation duration on cluster $n + 1$ after leaving cluster n (Rayner & Duffy, 1986). We also investigated *parafovea-on-fovea effects*, or the influence of cluster $n + 1$ on the processing of cluster n (Kennedy & Pynte, 2005; Kliegl et al., 2006). For parafovea-on-fovea analyses, we excluded clusters that preceded a target, appeared at the end of a line, or occurred before a skipped cluster, thereby omitting 18% of the data.

Participants fixated the majority of distractors, skipping less than 7.4%. Based on individual participants' fixation-duration distributions, we excluded fixations outside of $Q1 - (3 \times$ semi-interquartile) and $Q3 + (3 \times$ semi-interquartile) range as outliers. Because the data were right-skewed, we performed a logarithmic transform to make the distributions more normal. This meant that on average, fixations shorter than 82 *ms* and longer than 898 *ms* were removed, resulting in the loss of approximately 1.4% of the data. Data were analyzed using a linear mixed-effects (*lme*) model with participants and blocks (to separate the variance associated with the assignment of particular clusters to blocks) as random effects. *p*-values were estimated using Markov chain Monte Carlo sampling. Regression weights cannot be directly interpreted as effect sizes because analyses were performed on log-transformed measures; to increase transparency, estimated effect sizes and the means in Table 1 are from lme analyses of untransformed data. A backward model selection procedure was used to determine which interaction terms (if any) should be included as predictors, as necessary re-fitting reduced models and making comparisons using log likelihood ratio tests. Only the results of models selected by this procedure are reported here.

We examined whether first-fixation duration on a cluster was affected by number of exposures, gap size, and practice in the task (i.e., ordinal trial number). First-fixation durations were not reliably affected by the number of exposures ($b = -0.04$, $SE = 0.08$, $p = .94$) or practice ($b = -0.03$, $SE = 0.03$, $p = .48$). However, they decreased with increasing gap size ($b = -3.62$, $SE = 0.52$, $p < .01$).

Gaze duration decreased with more exposures ($b = -0.73$, $SE = 0.17$, $p < .01$), with the predicted change being approximately 1 *ms* for every additional exposure. Gaze duration also decreased with larger gap sizes and more practice in the task [gap size: ($b = -36.83$, $SE = 1.15$, $p < .01$); practice: ($b = -0.51$, $SE = 0.07$, $p < .01$)]. Similarly, total-viewing time decreased with more exposures ($b = -0.78$, $SE = 0.18$, $p < .01$), wider gaps ($b = -40.66$, $SE = 1.17$, $p < .01$), and more practice ($b = -0.85$, $SE = 0.08$, $p < .01$).

The number of fixations on a cluster during first-pass scanning showed no main effect of number of exposures ($b = 0.0007$, $SE = 0.001$, $p = 0.64$), but participants made fewer fixations on clusters with wider gaps ($b = -0.12$, $SE = 0.008$, $p < .01$) and with more practice in the task ($b = -0.003$, $SE = 0.0006$, $p < .01$). A gap size number of exposures interaction ($b = -0.0006$, $SE = 0.0003$, $p < 0.05$) indicated that repeated exposure to clusters with wider gaps was associated with a greater decrease in the number of fixations than clusters with narrower gaps. A gap size practice interaction ($b = 0.0003$, $SE = 0.0001$, $p < 0.01$) demonstrated that for wider gaps the effect of practice was associated with a smaller decrease in the number of fixations.

We examined whether characteristics of the preceding cluster affected first-fixation durations on the next cluster, i.e., spillover. Spillover was unaffected by the number of exposures ($b = 0.29$, $SE = 0.20$, $p = .06$), however there was a main effect of gap size ($b = 1.57$, $SE = 0.78$, $p < .05$), with longer fixations after clusters with wider gaps. This main effect was qualified by gap size number of exposures interaction ($b = -0.08$, $SE = 0.04$, $p < .05$), indicating that repeated exposure to clusters with wider gaps, but not narrower gaps, was associated with decreases in spillover. There was also a main effect of practice ($b = -0.10$, $SE = 0.04$, $p < .01$), with more practice in the task associated with less spillover.

Finally, we investigated whether characteristics of the upcoming cluster affected processing on the current cluster, i.e. *parafovea-on-fovea effects*. Gaze duration and the number of fixations on a cluster both increased with the gap size of the following cluster (GD: $b = 9.08$, $SE = 2.39$, $p < .01$; fixation count: ($b = 0.03$, $SE = 0.01$, $p < .01$). This effect was qualified by gap size practice interaction in both measures (GD: $b = -0.12$, $SE = 0.04$, $p < .01$; fixation count: $b = -0.0004$, $SE = 0.0001$, $p < .01$), such that practice reduced the effect of the upcoming cluster’s gap size. The effect of gap size was not reliable for the first-fixation duration or total-viewing time (FFD: $b = -0.09$, $SE = 0.57$, $p = .06$; TT: $b = 0.47$, $SE = 1.24$, $p = .56$).

Discussion

This study investigated the role of cognition in eye-movement behavior in a visual search task. Distractor clusters that were encountered more often had shorter gaze durations and total-viewing times, and received fewer fixations. These findings parallel word-frequency effects in reading (Inhoff & Rayner, 1986) and have several important theoretical implications. First, the effect of cluster frequency indicates that participants did not solely engage in letter-by-letter discrimination, but processed the clusters more holistically (McClelland & Rumelhart, 1981; Reicher, 1969). This is similar to a shift in word-processing associated with reading expertise: whereas novices may assemble words letter-by-letter, expert readers appear to process words as wholes (e.g., Ans et al., 1998). Second, these data suggest that frequency effects may emerge as a result of repeated exposure to a cluster, and more specifically, indicate a causal relationship between the number of exposures and the timing of saccadic programming. We hypothesize that the trigger to initiate saccadic programming in our experiment and reading corresponds to the access of information about a particular cluster or word from memory. In the current experiment, the to-be-accessed information is whether a cluster contains a target letter; in reading, it may correspond to a word's pronunciation and meaning. After only a few encounters, a cluster or word is only weakly represented in memory and its form and/or meaning is difficult to access, leading to longer saccadic latencies. But with more encounters, a cluster or word's representation becomes stronger and easier to access, leading to shorter saccadic latencies. This finding is therefore consistent with episodic theories of lexical access, according to which each encounter with a word increases its representational strength (Ans et al., 1998; Craik & Tulving, 1975; Goldinger, 1998; Reichle & Perfetti, 2003). The finding is also consistent with models of eye-movement control in which lexical access is the primary determinant of when the eyes move from one word to the next (Just & Carpenter, 1980; Reichle et al., 1998).

It is important to note that the current experiment's frequency effects arose from form frequency. This means that they should be similar to orthographic frequency effects, but smaller than word-frequency effects (cf., White, 2008). This is because word representations have multiple components (e.g., phonology, orthography, and semantics) and richer representations are accessed more quickly and successfully from memory (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Seidenberg & McClelland, 1989; Plaut, McClelland, Seidenberg & Patterson, 1996).

The present study replicated Williams and Pollatsek's (2007) gap-size effects on the fixated cluster, but additionally found spillover effects. These included a main effect of gap size and an interaction between gap size and the number of exemplars, which indicated that repeated exposures to clusters with wider gaps reduced spillover. This could indicate that participants engaged in a strategic trade-off between perceptual discrimination and memory access. That is, participants may have initially engaged in letter-by-letter discrimination for clusters with wider gaps because *C* versus *O* discrimination is relatively easy with wide gaps. This strategy is slow, however, and affords little parafoveal processing, thereby resulting in spillover[1]. As a cluster was encountered more often and its representation became stronger, participants may have relied more on memory access, thereby reducing spillover.

Similarly, the finding that practice reduced parafovea-on-foveal effects of gap size provides further evidence that participants began to gradually treat clusters as holistic units. The finding that fixations were longer and more numerous when the upcoming cluster was *easier* to process (i.e., had wider gaps) appears to contradict the finding of longer fixation durations with *increased* parafoveal processing difficulty (e.g., Kliegl et al., 2006). A possible explanation for the current finding is that some parafoveal *C* and *O* discrimination may be possible for clusters with wide gaps; in these cases, participants may have adjusted their attentional window to process the current and upcoming clusters simultaneously. Under these conditions, attentional resources would be divided and processing slowed. The interaction with practice could indicate that this divided-attention strategy was relatively inefficient and became less likely with practice.

Some previous visual search studies have observed *no* effect of word frequency on eye movements across distractor words (Rayner & Fischer, 1996; Rayner & Raney, 1996). However, in those studies, target-distractor discrimination only required detecting surface-

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[1] This account predicts the same interaction in gaze duration; analyses indicated such an interaction was marginally reliable ($p = .092$).

level perceptual differences (e.g., the target word *zebra* can be discriminated from most other words on the basis of its initial letter). In our task, the stimuli's homogeneity and high similarity to the target likely forced in-depth processing. This could have made strategies relying on memory access, and thus cognition, more effective and led to the observed reading-like eye movements. This explanation is consistent with other findings that the more deeply a scanning task engages cognition, the more similar eye-movement behavior is to reading (Kaakinen & Hyöna, 2010; Rayner, 1998; Reichle, Vanyukov, Laurent, Warren, 2008). It also complements findings that when readers are mind-wandering and thus not engaging cognition, fixations tend to be longer and less affected by cognitive variables (e.g., word frequency) (Reichle, Reineberg & Schooler, 2010).

Some have argued that word-frequency effects arise from perceptual tuning to familiar visual stimuli (McDonald et al., 2005), rather than as a consequence of memory access during lexical processing. The results of the current study do not rule out a perceptual tuning account, if tuning for specific exemplars becomes more precise with repeated encounters. However, the mechanisms of perceptual tuning are not well-specified in the literature, and within the context of many episodic word-processing models (e.g., Ans et al., 1998; Reichle & Perfetti, 2003), perceptual tuning and memory access are difficult, if not impossible, to dissociate. The current experiment brings us a step closer to demonstrating cognitive effects on eye movements by showing effects of memory accessibility in addition to effects of stimulus discriminability. Future research may provide more compelling evidence for the role of cognition in eye movement behavior by demonstrating predictability effects in this paradigm.

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Figure 1.

Example target present trial (target is located in the 3rd letter cluster).

Table 1

Estimated means for eye movement measures on distractor clusters (fixation durations in ms)

	1st exposure				50th exposure			
	Gap size 2	**Gap size 4**	**Gap size 6**	**Gap size 8**	**Gap size 2**	**Gap size 4**	**Gap size 6**	**Gap size 8**
First fixation	332	325	318	310	330	323	316	309
Gaze duration	792	719	645	571	756	683	609	535
Total-viewing time	866	784	703	622	828	746	665	584
Number of fixations on first pass	2.7	2.4	2.2	2.0	2.6	2.3	2.0	1.8
Spill over	343	346	349	352	350	345	341	336
Parafovea-on-fovea effects (gap size is of upcoming cluster)	1st trial				116th trial			
Gaze duration	641	658	676	694	624	616	607	598
Total-viewing time	718	726	733	741	643	637	631	625
Number of fixations on first pass	2.2	2.3	2.3	2.4	2.1	2.1	2.1	2.0