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Frequency and Predictability Effects in Eye Fixations for Skilled and Less-Skilled Deaf Readers

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Abstract

The illiteracy rate in the deaf population has been alarmingly high for several decades, despite the fact that deaf children go through the standard stages of schooling. Much research addressing this issue has focused on word-level processes, but in the recent years, little research has focused on sentence-levels processes. Previous research (Fischler, 1985) investigated word integration within context in college-level deaf and hearing readers in a lexical decision task following incomplete sentences with targets that were congruous or incongruous relative to the preceding context; it was found that deaf readers, as a group, were more dependent on contextual information than their hearing counterparts. The present experiment extended Fischler's results and investigated the relationship between frequency, predictability, and reading skill in skilled hearing, skilled deaf, and less-skilled deaf readers. Results suggest that only less-skilled deaf readers, and not all deaf readers, rely more on contextual cues to boost word processing. Additionally, early effects of frequency and predictability were found for all three groups of readers, without any evidence for an interaction between frequency and predictability.

Keywords

Deaf readers; eye movements; reading skill; predictability effects; frequency effects

Much research has been conducted with deaf readers, children and adults, as they experience, as a population, high levels of illiteracy relative to the general population (see Kelly & Barac-Cikoja, 2007 for a review). A large proportion of the research has focused on word-level processes (Bélanger, Baum & Mayberry, 2012a; see Kelly & Barac-Cikoja, 2007; Mayberry, del Giudice & Lieberman, 2011), and also on comprehension difficulties related to syntactic complexity (Kelly, 2003; Quigley, Wilbur, Power, Montanelli & Steinkamp, 1976). Few studies, however, have investigated word processing in relation to sentence context, though one such study (Fischler, 1985) investigated word integration within context in college-level deaf and hearing readers. The participants were asked to perform a lexical decision task following incomplete sentences. Target words were congruous, unlikely, or incongruous with the preceding context. Deaf participants responded faster to congruous words than to incongruous words, indicating that they constructed the meaning of the sentence appropriately, and showed inhibition when a target word was not compatible with that meaning. Overall, the congruency effect found for the deaf readers was larger than for the hearing control group, suggesting that deaf readers rely more on context than hearing readers do. However, the deaf participants' scores on the reading test they were administered ranged from the 8^{th} to the 99^{th} percentile, indicating a wide range of reading skill, even though they were college students. Information on reading-level was not reported

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for the hearing participants, but given that they were all Psychology undergraduates it may be expected that their reading skills were more homogeneous than that of the deaf readers. Because of the wide range of reading levels in the group of deaf readers and the prevalence of reading difficulties in this population, it is likely that the group was more representative of less-skilled readers than skilled readers. Nevertheless, Fischler concluded: “that the deaf students as a group appear to use sentence contexts to anticipate particular words to a greater extent than do the hearing students” (p.215).

To date, little work has investigated reading processes of deaf readers while taking into account their reading skill (instead of their educational level) by comparing skilled and less-skilled readers based on standardized reading measures. Previous research however has shown that skilled deaf readers show marked qualitative differences in their eye movement characteristics and reading processes relative to skilled hearing readers. Specifically, skilled deaf readers have a wider perceptual span, make longer saccades, and regress back into the text less often than skilled hearing readers do (Bélanger, Slattery, Mayberry, & Rayner, 2012b), suggesting that skilled deaf readers are very efficient readers. Additionally, skilled deaf *and* less-skilled deaf readers have been shown to process words without activating phonological codes (Bélanger et al., 2012a; Bélanger, Mayberry & Rayner, 2013) suggesting that the activation of these codes (or not) is not a determinant of poor reading skills in the deaf population. This more fine-grained analysis of deaf readers’ eye movement behavior and word processing suggest that it is important to investigate and compare groups of skilled and less-skilled deaf readers. It is furthermore essential to specifically study skilled deaf readers and compare them to skilled hearing readers in order to determine the similarities and differences in reading processes between these two groups. This will make it possible to establish a reading model specifically based on skilled deaf readers, which can then be used to inform reading education for deaf children. Thus, the goal of the present experiment was to compare skilled deaf readers to skilled hearing readers, and then to compare skilled deaf readers to less-skilled deaf readers. Indeed, in relation to Fischler’s results, it remains to be determined whether all deaf readers rely more on context than hearing readers or whether this effect varies according to their reading skills.

In hearing readers, effects of frequency and predictability have both been well documented and both have a strong influence on readers’ eye movements (see Rayner, 1998, 2009 for reviews). High frequency words are read faster and are skipped more often than low frequency words (Inhoff & Rayner, 1986, Rayner, Ashby, Pollastek, & Reichle, 2004; Rayner & Duffy, 1986; Rayner, Sereno, & Raney, 1996) and highly predictable words are also read faster and skipped more often than unpredictable words (Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2005; Rayner, Ashby, Pollatsek & Reichle, 2004; Rayner & Well, 1986; Rayner, Slattery, Drieghe, & Liversedge, 2011). The two variables have been shown to have an additive effect (Ashby, Rayner, & Clifton, 2005; Gollan, Slattery, Goldenberg, Van Assche, Duyck, & Rayner, 2011; Hand, Miellet, O’Donnell, & Sereno, 2010; Rayner et al., 2004; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Slattery, Staub, & Rayner, 2012) on eye fixation times on a target word. An interaction between frequency and predictability has been reported with respect to the probability of skipping target words (Gollan et al., 2011; Hand et al., 2010; Rayner et al., 2004), though the nature of the interaction has not been consistent across the experiments[1].

In addition, frequency and predictability effects have been shown to be modulated by reading skill (Ashby et al., 2005; Hyönä & Olson, 1995; Jared, Levy, & Rayner, 1999). In line with an interactive-compensatory model of reading, when word reading is not fully automatized, less-skilled readers appear to rely more on contextual information than skilled readers do (West & Stanovich, 1978; Stanovich, West, & Feeman, 1981). Ashby et al.

(2005) investigated frequency and predictability effects in adults with high or average reading skills and found that skill interacted with frequency. Interestingly, in early eye movement measures (gaze durations) of word processing, the frequency effect was much larger (40 ms) for the average readers than for the skilled readers (11 ms; Experiment 1). A complex relation between reading level, frequency, and predictability was also found in re-reading measures. Average readers regressed back to the target words more often when they were high-frequency and predictable than when they were low-frequency and predictable, whereas skilled readers regressed back more often to the targets only when they were low-frequency and unpredictable relative to the other conditions. Ashby et al. however did not discuss this “inverse frequency effect” (p.1076) found for the average readers in detail, but instead concentrated on the fact that the average readers regressed back to the targets more often than the skilled readers did when the targets were in unpredictable contexts. They suggested that this might be due to a delayed effect of mismatching information between contextual cues and bottom-up word-level cues.

In the present experiment we investigated the eye movements of skilled hearing readers (SKH), skilled deaf readers (SKD), and less-skilled deaf readers (LSKD) in order to determine whether all deaf readers show larger predictability effects than hearing readers or whether predictability is also modulated by reading level in the deaf population. Additionally, we investigated effects of word frequency in deaf readers to determine whether it is modulated by reading level (Ashby et al., 2005). Finally, we further investigated the relationship between frequency and predictability. We thus created stimuli in which frequency of the target words (high vs. low) was crossed with contextual constraints (predictable or neutral context preceding the target words).

We hypothesized that frequency effects would be found for all three groups of readers, but that LSKD readers would show a larger frequency effect than the SKH and SKD readers. We also hypothesized that all groups of readers would show additive effects of frequency and predictability in early reading times (first fixation duration and gaze duration) and in later measures (total time). As for the presence of an additive or interactive effect of predictability and frequency in the skipping rates, we had no predictions, as results have been varied in the literature. Finally, we hypothesized that the LSKD readers, but not the SKD readers, would show greater reliance on contextual constraints. Standard reading level effects on eye movement measures were also expected. Less-skilled deaf readers were expected to spend longer viewing the target words, to skip them less often, and to regress back into prior text more often than skilled readers (deaf or hearing).

Methods

Participants

Forty severely to profoundly deaf adults (hearing loss > 71dB in the better ear) from the San Diego Deaf community participated in the study. They were recruited because they used American Sign Language (ASL) as their main communication mode and had been exposed

[1]Recently, Hand et al.(2010) investigated the Frequency × Predictability interaction as a function of launch sites of fixations before fixating the targets. They found a significant interaction in the single fixation duration data between frequency and predictability only when the launch sites from the words preceding the targets were 1–3 characters away from the target. This interaction suggested that predictability effects were larger for low-frequency words than for high frequency words. When the launch sites from the word before the targets were 4–6 characters away from the target, the interaction was also significant but reversed with a larger predictability effect for the high frequency words than for the low-frequency words. The interaction for launch sites even further away from the targets (7–9 characters) was not significant. Finally, a Frequency by Predictability interaction was found in the skipping data, suggesting, contrary to what was found for the fixation duration data, that only the high frequency words were affected by context predictability. Slattery et al. (2012), however, questioned Hand et al.’s statistical analyses, performed similar analyses (Frequency × Predictability × Launch site) on two data sets but did not replicate Hand et al.’s results.

to it for a minimum of 10 years, and also because they were mostly born deaf or became deaf before the age of two (3/40 participants became deaf between 3 and 10 years). Deaf participants were aged between 20 and 45 years (*M* = 30 years). Twenty native English speakers served as a control group. They were aged 21 to 43 years (*M* = 29 years) and were all skilled readers. All participants had normal or corrected-to-normal vision and received financial compensation for their participation.

Background Measures

All participants completed the *Peabody Individual Achievement Test-Revised* (PIAT-R; Markwardt, 1989) in order to determine their reading level. Standard scores on this test were used to split the deaf participants into two groups (skilled and less-skilled readers): skilled deaf readers were matched as closely as possible on reading level to skilled hearing readers and the remainder of the deaf participants were placed in the less-skilled deaf reader group (hence the slightly different *n*s for each group). A comparison of the reading level of skilled hearing readers ($n = 20$; $M = 85$; $SD = 6.8$; Range = 72–95; Grade level equivalent = 11th grade), skilled deaf readers ($n = 18$; $M = 82$; $SD = 5.5$; Range = 74–93; Grade level equivalent = 10th grade) and less-skilled deaf readers ($n = 22$; $M = 68$; $SD = 4.1$; Range = 57–73; Grade level equivalent = 6th grade) yielded the expected group effect ($F(2, 54) = 46.49$, $p < .0001$, $\eta_p^2 = .63$)[2]. Less-skilled deaf readers differed significantly from SKH readers ($p < .0001$) and SKD readers ($p < .0001$). As they were specifically matched on reading-level, skilled hearing readers and skilled deaf readers did not differ on this variable ($p = .22$). Non-verbal IQ was also assessed for all participants via the Picture Completion, Picture Arrangement, and Block Design subtests from the performance scale of the *Wechsler Adult Intelligence Scale—Revised* (Wechsler, 1981). Skilled hearing readers ($M = 11.4$; $SD = 1.7$), SKD ($M = 11.3$; $SD = 1.4$) and LSKD readers ($M = 10.5$; $SD = 1.6$) did not differ on this measure (mean scale scores for the three tests; $F(2, 54) = 1.86$, $p > .16$, $\eta_p^2 = .06$). Finally, language background information was gathered for all deaf readers. Skilled deaf readers acquired ASL at a younger age than LSKD readers ($M = 4.5$ and $M = 8$, respectively; $p = .04$), but both groups did not differ in age of English acquisition ($M = 1.3$ and $M = 2.8$, respectively; $p = .08$).

Stimuli

Sixty-four target words (32 high frequency and 32 low frequency words) were embedded in two different sentence frames: neutral or predictable contexts, creating four conditions (see Table 1 for example sentences). We made sure that words were not in sentence-initial or sentence-final position. Targets were nouns, were five to six letters long, were matched on number of phonemes ($p = .14$) and number of syllables ($p = .16$) across frequency conditions. The high frequency words occurred 96 times per million (Range 18–404) and the low frequency targets occurred 11 times per million ($p = < 001$; Range 1–18; determined from the CELEX count using N-Watch software; Davis 2005). Words were also chosen to be familiar (even if low frequency), so that even the participants with the lowest reading level would comprehend them. For this same reason, care was taken to create sentences with a simple syntactic structure to avoid potential reading difficulties associated with syntactic processing (Kelly & Barac-Cikoja, 2007 review). To ensure that the neutral and predictable contexts were well constructed, sentences were normed in a cloze task by 20 undergraduates who did not take part in the experiment. Participants were provided with the first part of the sentence up to, but not including, the target. They were asked to provide the first word that

[2]The goal of the present experiment was to specifically compare skilled deaf readers to skilled hearing readers and then to compare less-skilled deaf readers to the skilled deaf readers. We therefore did not include a group of less-skilled hearing readers. Additionally, note that it would be unlikely to find a group of non-dyslexic hearing readers matched on age, reading level (6th grade level) and non-verbal IQ, to the less-skilled deaf readers.

came to mind to best continue the sentence. The mean probability of completing the sentence with the low-frequency target words was 0.01 for the neutral contexts and 0.84 the predictable contexts. For the high-frequency targets, these values were 0.03 and 0.79, respectively. Overall, the mean probability for the neutral sentences was significantly lower (0.02) than that of predictable sentences (0.82; $p = < 001$).

Apparatus

Eye movements were recorded with an EyeLink 1000 eyetracker (SR Research, Kanata, Ontario, Canada) while participants were reading. Participants were seated 60 cm from a 22 inch NEC MultiSync FP1370 monitor (refresh rate of 150Hz) on which they read single-line sentences. Head movements were minimized with the use of a chinrest and headrest.

Procedure

The UMass *Eye Track 0.7.10h* software (Stracuzzi & Kinsey, 2006) was used to present the sentences in black 14pt *Courier New* font on a light grey background; 3.4 letters equalled 1° of visual angle. Viewing was binocular, but eye movements were recorded from the right eye only. All sentences were displayed on a single line.

Before the experimental session, participants completed the background tests. For the experimental reading task, participants were instructed to read silently while their eye movements were monitored. A 3-point calibration procedure was performed prior to the experimental task. The participants then read the 64 experimental sentences. Each participant saw every target word only once in one of two types of contextual constraint: neutral of predictable. Order of presentation of the experimental sentences and 72 fillers was randomized for each participant. The equipment was recalibrated throughout the experiment when necessary. After 28% of the trials, yes/no comprehension questions were asked and participants responded by pressing buttons on a keypad. SKH, SKD, and LSKD readers answered correctly 91%, 90%, and 86% of the time, respectively ($F(2, 57) = 4{,}75$, $MSE = 36.87$, $p =.01$). A Tukey HSD *posthoc* test revealed that the LSKD readers were not as accurate as the SKH readers ($p < .05$), but that they did not differ significantly from the SKD readers ($p > .05$). The SKH and KSD readers did not differ in their response accuracy ($p > .05$).

Analysis

A number of standard eye movement measures (Rayner, 1998, 2009) were analyzed and are presented below, including *first fixation duration* (the duration of the first fixation on a target word), *gaze duration* (the sum of fixations on the target word before the eyes move away from the target), *probability of skipping* the target word on first-pass reading, *total time* (the sum of all fixations on the target word including regressions), and *regressions in* (the probability, calculated over all trials, that the eyes regress back to the target word after having moved past it). Trials were excluded if (1) a blink occurred just before, on, or just after the target word (1%), or if (2) fixation time was more than 2.5 standard deviations above the mean for each participant (equal to or less than 1.4% of the data per group for first fixations and gaze durations). Additionally, fixations shorter than 80 ms and within one letter of another fixation were combined (2%).

Analyses were performed with linear-mixed effects models and run with the lme4 package (Bates, Maechler, & Dai, 2009), available in the R environment (R Development Core Team, 2008). Generalized linear mixed models (GLMM) were used to analyze skipping and refixations data (binary variables). For each variable, a model was specified with participants and items as crossed random effects (Baayen, 2008) with group (SKH, SKD, LSKD), frequency (high vs. low), and predictability (predictable vs. neutral) as fixed factors.

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Frequency and predictability were within-subject variables and were centered to reduce collinearity. In order to examine the difference between the SKH and SKD readers and between the SKD and LSKD readers, two successive difference contrasts (Venables & Ripley, 2002) were set up within the models. Because of the successive difference contrasts with the group variable, the model produced separate interaction terms for each of the contrasts (SKH vs. SKD and SKD vs. LSKD), yielding two three-way interactions, but also two two-way interactions for the frequency variable and two two-way interactions for the predictability variable. Regression coefficient estimates (b), standard errors (SE), and *t*-values (*z*-value for the skipping and refixations data) are reported. A two-tailed criterion ($|t| \geq 1.96$; $|z| \geq 1.96$) was used to determine significance. Models were first run with random slopes, including group, predictability, frequency, and their interactions, and reduced to their simplest fit (random intercepts) when possible, unless otherwise specified in the *Results* section, via model comparisons using likelihood ratio tests. Non-significant interactions were also removed from the models following this procedure if they did not increase the models log-likelihood (the results of the full models are presented in the Appendix). Separate analyses were also performed for each group separately to better unpack significant interactions.

Results and Discussion

First Fixation Duration

The analyses of first fixations revealed an effect of predictability, with targets in the neutral sentence contexts ($M = 225$ ms) fixated for a longer time than targets in the predictable sentence contexts ($M = 213$ ms; $b = 6.55$, SE = 3.11, $t = 2.10$). There was also an effect of frequency with low frequency targets (222 ms) fixated for a longer time than high frequency targets ($M = 216$ ms) $b = 11.16$, SE = 3.11, $t = 3.58$). The three-way interactions were not significant ($t < 0.16$), and neither were the two-way interactions ($t < 1.24$; including the Frequency × Predictability interaction: $b = 5.64$, SE = 6.23, $t = 0.91$), except for the SKD vs. LSKD × Predictability interaction, which approached significance ($t = 1.77$).

As expected based on their reading level, LSKD readers' first fixations ($M = 235$ ms) were significantly longer than SKD readers' fixations ($M = 212$ ms; $b = 21.33$, SE = 8.94, $t = 2.38$). Neither group of skilled readers, however, differed in their fixation times on the target words ($t = 0.41$; SKH: $M = 208$ ms; SKD: $M = 212$ ms).

Gaze Duration

The analyses of gaze duration revealed a similar pattern to that of first fixation duration: a significant effect of frequency was found ($b = 9.78$, SE = 4.30, $t = 2.28$), where high frequency targets were fixated for a shorter time (224 ms) than low frequency targets were (254 ms), along with a significant effect of predictability ($b = 19.09$, SE = 4.30, $t = 4.44$), where targets in predictable contexts were read faster (239 ms) than when they were inserted in a neutral context (259 ms). Again, both three-way interactions were not significant, ($t < 0.76$), nor were the Frequency × Predictability interaction ($t < 1.08$) and the Group × Frequency interactions ($t < 0.95$). However, the SKD vs. LSKD × Predictability interaction was significant ($b = 20.51$, SE = 7.99, $t = 2.57$) indicating that the effect of predictability was larger for the LSKD readers than it was for the SKD readers. The equivalent interaction for both groups of skilled readers, SKH vs. SKD × Predictability, was not significant, indicating that the two groups of skilled readers did not differ on the predictability measure ($t < 0.06$). The two interactions between groups and frequency were not significant ($t < 0.95$). Similar to what was found for first fixations, gaze durations were longer for the LSKD readers ($M = 276$ ms) than for the SKD ($M = 230$ ms; $b = 42.95$, SE = 11.72, $t = 3.66$), but the SKD readers and SKH readers ($M = 236$ ms) did not differ ($t = -0.48$).

The interaction between predictability and the two groups of deaf readers was unpacked by two follow-up analyses on the gaze duration data, one for each group, with frequency and predictability as fixed variables. Models also included frequency and predictability as random slopes and were reduced to simpler models with random intercepts following the method described earlier, except for the SKD readers' data analysis where the random slope for Predictability x Subject remained in the model. The analysis for the SKD readers revealed a significant effect of frequency ($b = 13.77$, SE = 5.94, $t = 2.32$). The effect of predictability was not significant ($b = 11.79$, SE = 9.20, $t = 1.28$), neither was the Frequency × Predictability interaction ($b = 14.03$, SE = 11.86, $t = 1.18$). The LSKD readers on the other hand showed a highly significant effect of predictability ($b = 32.60$, SE = 6.12, $t = 5.32$), thus suggesting that they are more sensitive to contextual information than SKD readers are. The effect of frequency did not quite reach significance ($b = 10.14$, SE = 6.12, $t = 1.66$) and the Frequency × Predictability interaction also did not reach significance ($b = 1.91$, SE = 12.25, $t = 0.16$)

With respect to the two standard early measures of processing (first fixation duration and gaze duration), we found strong effects of frequency and predictability. As expected from previous research, there was no hint of an interaction of Frequency by Predictability. Importantly, however, and as expected by their reading level, the LSKD readers showed stronger effects of contextual constraint than SKD and SKH readers did. We next report the skipping probability of the target words.

Skipping probability

Skipping probability is a reliable indicator of processing difficulty and is sensitive to word frequency (Rayner et al., 1996). Mirroring the effects found for early fixation durations, significant effects of frequency ($b = -0.28$, SE = 0.13, $z = -2.10$) and predictability ($b = -0.51$, SE = 0.14, $z = -3.75$) were found where high frequency targets were skipped more often (19% of the time) than low frequency targets (15%) and targets in the predictable condition were also skipped more often (20%) than when they were inserted in neutral sentences (14%). Overall, the three groups did not differ in their probability of skipping a target. LSKD readers ($M = 15\%$) did not skip targets more often than SKD readers did ($M = 19\%$, $z = -0.92$). Interestingly, the SKD readers skipped words slightly more often than SKH readers did (17%), but this difference was not significant ($z = 0.46$). None of the interactions were significant (zs < 1.15).

Total Time

The analysis of total fixation times revealed that the effect of predictability persisted over time with predictable targets fixated for less time overall (274 ms) than targets in neutral contexts (306 ms; $b = 29.30$, SE = 7.02, $t = 4.18$). The frequency of targets, however, did not influence total fixation times ($t = 0.47$). As was found for the earlier fixation duration measures, an interaction for the SKD vs. LSKD × Predictability was found ($b = 37.45$, SE = 12.67, $t = 2.96$). The equivalent interaction between the skilled readers (SKH vs. SKD × Predictability) was not significant however ($t = -0.62$). Similar to previous measures, no other interaction was significant (ts < 0.70).

Separate analyses for the SKD and LSKD readers revealed that for the SKD readers there was no significant effect of frequency ($t = 0.55$), predictability ($t = 1.57$), and no interaction between these two factors ($t = 0.22$). The LSKD readers showed no influence of target frequency on this later processing measure either ($t = 0.69$), but a robust predictability effect was still present ($b = 51.21$, SE = 11.13, $t = 4.60$). The Frequency × Predictability was not significant ($t = 0.52$).

Regressions In

Surprisingly, the overall proportion of regressions back to the target word after the eyes moved past it was higher for high frequency targets (10%) than it was for low frequency targets (M = 8%; b = −0.33, SE = 0.16, z = −2.09), but predictability did not affect the proportion of regressions into the target (b = 0.22, SE = 0.16, z = 1.40). The two-way and three-way interactions were not significant (zs < 1.40), except for the SKD vs. LSKD × Predictability interaction, which, as for the previous measures, was highly significant (b = 0.85, SE = 0.33, z = 2.58). Overall, LSKD readers (M = 10%) did not regress back to the target significantly more than SKD readers did (M = 9%; z = −0.27), and SKD readers did not regress back to the target more than the SKH readers either (M = 9%; z = −0.37).

Separate analyses for the SKD and LSKD readers in relation to the interaction with predictability revealed that SKD readers' regressions back to the targets were not influenced by frequency (z = −1.24) or predictability (z = −0.78). The interaction between these two factors was also non-significant (z = −0.48). The LSKD readers on the other hand, showed a highly significant effect of predictability (b = 0.85, SE = 0.33, z = 2.58), where predictable targets were regressed back to less often overall (M = 7%) than when they were inserted in a neutral context (M = 12%). The effect of frequency was not significant (z = −0.83) and neither was the Frequency × Predictability interaction (z = 1.50).

General Discussion

The SKH readers presented the standard pattern of eye movements found in relation to frequency and predictability. They fixated words for a longer time and skipped targets less often when targets were low frequency and when they were inserted in neutral contexts than when they were in predictable contexts. Additionally, as in prior research, no interactions between frequency and predictability were found in any of the measures (Ashby et al., 2005; Gollan et al., 2011; Rayner et al., 2001, 2004, 2006; Slattery et al., 2012).

More in line with the focus of this paper, the results for the deaf readers revealed patterns of eye movements that were mostly similar to that of the SKH readers. LSKD readers had longer fixation times than did the SKH and SKD readers, revealing the expected reading-level differences (Ashby et al., 2005; Rayner, 1998). Both groups of deaf readers, like the SKH readers, showed early effects of predictability, suggesting that preceding context could be constraining enough to speed up target processing, but also to generate (unconscious) predictions about an upcoming word while still in parafoveal vision, as evidenced by the skipping data. Additionally, both groups of deaf readers showed standard early effects of frequency. Importantly, the interactions between group and predictability were not significant between the SKH and SKD readers, but were between the SKD and LSKD readers in all measures presented above. In other words, the LSKD readers' fixation times on the target and the probability to regress back to that target were much more influenced by the preceding semantic context than they were for the two groups of skilled readers.

Interestingly, Group by Frequency interactions were not found in any of the measures reported. In their experiment comparing hearing skilled and average readers, Ashby et al. (2005) found weak interactive patterns in first fixation duration and gaze duration, where average readers showed greater frequency effects than skilled readers did. The present data did not show this pattern of effects and this is potentially due to the fact that our manipulation covered a smaller range of frequencies across conditions (high = 96 per million, and low = 11 per million) than what has been tested in prior work (high = 150 per million and low = 5 per million in Ashby et al., 2005 for example). Words that were high frequency or low frequency and familiar were chosen for the present experiment in order to ensure that even readers with the lowest reading levels would know all the words presented in the experiment as it was important that all participants read for comprehension. With a greater range of frequencies between conditions, these effects might emerge however, especially since they were found between college-level skilled and average readers for whom the range of reading-levels was clearly much smaller between the groups (Ashby et al., 2005) than the skill difference found between the groups in the present experiment.

The *regressions-in* measure also revealed a significant "inverse frequency effect". Readers regressed significantly more often to high frequency targets than to low frequency targets. A similar pattern was also reported by Ashby et al. (2005). Indeed, they found that average readers regressed more often to high frequency predictable targets than to low frequency predictable targets. The pattern of results found for the regressions back to the target words in the present study is somewhat in line with recent work by Bicknell and Levy (2011), who reported that regressions to a word were more probable when the word was longer, less predictable, and *more frequent*. Interestingly, the inverse frequency effect did not vary according to reading level in the present experiment and was not only confined to the predictable condition as in Ashby et al. (2005). Because regressions back to the target are also a function of the probability of skipping the target (Vitu & McConkie, 2000), the fact that the three groups of readers did not differ in terms of this inverse frequency effect may be related to the fact that they all skipped predictable targets more than targets in a neutral sentence.

Finally, previous work by Bélanger and colleagues has shown that reading processes in deaf readers can be qualitatively different than that of hearing readers. We have previously shown that SKD readers are extremely efficient at processing perceptual and orthographic information. They have a wider perceptual span, make longer saccades, and regress back into the text less often than SKH readers do (Bélanger et al., 2012b). In the present experiment, there was also evidence, though weak, that SKD readers are very efficient readers: they skipped words numerically (but not significantly; $M = 20\%$) more often than SKH ($M = 17\%$) and LSKD readers ($M = 16\%$) did, but regressed back into the text no more than the other two groups did ($M = 9\%$ for all groups), even though they did not differ from the SKH readers on early fixation durations. This suggests that SKD readers may be more efficient than SKH readers at picking up lexical information from the parafovea and at successfully processing words while they are foveated. This suggestion is in line with Bélanger et al.'s (2012b) findings. Note also that LSKD readers skip words just as often as SKH readers do and yet, they do not regress back to them more often. This is counterintuitive considering that the LSKD readers read at a much lower reading level (6^{th} Grade) than the SKH readers did (11^{th}). Thus LSKD readers, though they take longer to process words, also appear to be quite efficient at processing these words as they do not need to go back to them as often as may have been predicted by their reading level.

The fact that only less-skilled deaf readers make greater use of contextual cues provides a more refined portrait of reading processes in the deaf population as previously offered by Fischler's (1985) work, which suggested that all deaf readers benefited more from contextual cues than did hearing readers. In the present experiment, contrary to Fischler's study, groups of skilled readers, hearing or deaf, were matched on reading level, allowing for a better comparison. Crucially, both groups of skilled readers, SKH and SKD readers, did not differ in the size of the benefit they obtained from rich contextual cues. In this sense, there were no qualitative differences between hearing and deaf readers in that the effects of predictability were solely determined by reading skill (as shown by the difference between the SKD and LSKD readers), and not by hearing status (deafness; because there was no difference between the SKH and SKD readers), as might have been inferred from Fischler's conclusions.

When placed within an interactive-compensatory view of reading, greater use of semantic context is attributed to the lack of automaticity during word recognition, thus context is used to boost word recognition (Stanovich, 1984). It is important to keep in mind that deaf individuals' reading difficulties appear *not* to be related to the fact that they do not activate phonological codes during reading. Indeed, previous results suggest that *both* skilled and less-skilled deaf readers do not activate phonological codes during reading (Bélanger et al., 2012; Bélanger et al., 2013), suggesting that phonological code activation is not at the crux of the less-skilled readers' difficulties. The present results point to a need for compensation in word recognition automaticity for the less-skilled deaf readers from a greater use of context (i.e. less-skilled deaf readers' reading times for target words were much faster when the context helped predict the upcoming target than when it didn't), but difficulties likely do not lie in their ability to activate phonological codes when processing written words. Our data, at present, rather reveal that skilled deaf and less-skilled deaf readers, though matched on every other background measure, acquired ASL at different ages. This may be a hint as to where reading difficulties may originate from. Indeed, though both groups of deaf readers acquired English at a comparable age (see the *Background Measures* section), skilled deaf readers acquired ASL much earlier than less-skilled deaf readers did. Age of ASL acquisition has been tightly linked to later language proficiency and reading ability in the deaf population (Chamberlain & Mayberry, 2008; Mayberry et al., 2011; Mayberry, Lock, & Kazmi, 2002), thus our results may point to the fact that earlier ASL acquisition, and greater general language ability, might be a determinant of reading achievement in young deaf readers (Mayberry et al., 2011).

In sum, our experiment presents a pretty standard portrait of eye movement behaviors dictated by frequency and predictability in hearing readers, as expected, but also in deaf readers. Effects of frequency were found for all groups of readers, along with robust effects of predictability, and no interaction between the two variables, supporting the notion that each variable affects a different aspect of word processing (Ashby et al., 2005; Rayner et al., 2001, 2004, 2006; Slattery et al., 2012). LSKD readers also showed the classic reading-level differences found between skilled and less-skilled readers (Ashby et al., 2005; see Rayner, 1998 for a review). Crucially, LSKD readers fixated words for a longer time than did skilled readers (hearing or deaf), but most importantly, in line with an interactive-compensatory view of reading (Ashby et al., 2005; Stanovich, 1984; Stanovich et al., 1981; West & Stanovich, 1978), LSKD readers showed a greater effect of context predictability on word processing than the SKD did.

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Appendix

First Fixation Durations - Full LMM Model with Random Intercepts*

	b	*SE*	*t-value*
Group SKH-SKD	3.74	9.14	0.41
Group SKD-LSKD	21.33	8.94	2.38
Frequency	6.55	3.11	2.10
Predictability	11.16	3.11	3.58

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First Fixation Durations - Full LMM Model with Random Intercepts*

	b	*SE*	*t-value*
Group SKH-SKD × Frequency	−3.29	5.12	−0.64
Group SKD-LSKD × Frequency	8.88	5.00	1.77
Group SKH-SKD × Predictability	0.77	5.12	0.15
Group SKD-LSKD × Predictability	6.22	5.00	1.24
Frequency × Predictability	5.64	6.23	0.91
Group SKH-SKD × Frequency × Predictability	1.64	10.23	0.16
Group SKD-LSKD × Frequency × Predictability	−2.10	10.00	−0.21

*Note that the results of the LMMs presented in the Appendix are from the full models and the estimates, standard errors and t-values for group contrasts, frequency and predictability presented in the text may be slightly different. Indeed, when the interactions where not significant in the full models presented here, they were removed from the models. The data from the reduced models is at times presented in the text.

Gaze Durations - Full LMM Model with Random Intercepts

	b	*SE*	*t-value*
Group SKH-SKD	−5.77	11.98	−0.48
Group SKD-LSKD	42.95	11.72	3.66
Frequency	9.69	4.29	2.26
Predictability	19.03	4.29	4.43
Group SKH-SKD × Frequency	7.76	8.19	0.95
Group SKD-LSKD × Frequency	−2.92	7.99	−0.37
Group SKH-SKD × Predictability	0.59	8.19	0.07
Group SKD-LSKD × Predictability	20.60	7.99	2.58
Frequency × Predictability	9.74	8.58	1.13
Group SKH-SKD × Frequency × Predictability	1.45	16.36	0.09
Group SKD-LSKD × Frequency × Predictability	−12.12	15.97	−0.76

Gaze Durations - Full LMM Model with Random Slope (Predictability × Subject) - Skilled Deaf Readers

	b	*SE*	*t-value*
Frequency	13.60	5.93	2.29
Predictability	11.73	9.18	1.28
Frequency × Predictability	14.03	11.86	1.18

Gaze Durations - Full LMM Model with Random Intercepts – Less-skilled Deaf Readers

	b	*SE*	*t-value*
Frequency	10.14	6.13	1.66
Predictability	32.60	6.12	5.32

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Gaze Durations - Full LMM Model with Random Intercepts – Less-skilled Deaf Readers

	b	***SE***	***t-value***
Frequency × Predictability	1.91	12.25	0.16

Skipping Probability - Full LMM Model with Random Intercepts

	b	***SE***	***z-value***	***p-value***
Group SKH-SKD	0.17	0.35	0.49	0.63
Group SKD-LSKD	−0.34	0.34	−0.99	0.32
Frequency	−0.29	0.14	−2.11	0.04
Predictability	−0.50	0.14	−3.72	<0.001
Group SKH-SKD × Frequency	0.23	0.23	1.00	0.32
Group SKD-LSKD × Frequency	−0.09	0.23	−0.40	0.69
Group SKH-SKD × Predictability	0.01	0.23	0.03	0.98
Group SKD-LSKD × Predictability	−0.27	0.23	−1.16	0.25
Frequency × Predictability	−0.07	0.27	−0.24	0.81
Group SKH-SKD × Frequency × Predictability	−0.20	0.46	−0.44	0.66
Group SKD-LSKD × Frequency × Predictability	−0.05	0.46	−0.11	0.91

Total Time - Full LMM Model with Random Intercepts

	b	***SE***	***t-value***
Group SKH-SKD	−2.23	20.91	−0.11
Group SKD-LSKD	61.95	20.45	3.03
Frequency	3.20	7.04	0.45
Predictability	29.27	7.04	4.16
Group SKH-SKD × Frequency	9.10	12.99	0.70
Group SKD-LSKD × Frequency	1.85	12.67	0.15
Group SKH-SKD × Predictability	−7.98	12.99	−0.61
Group SKD-LSKD × Predictability	37.39	12.67	2.95
Frequency × Predictability	7.76	14.07	0.55
Group SKH-SKD × Frequency × Predictability	−3.00	25.96	−0.12
Group SKD-LSKD × Frequency × Predictability	8.78	25.31	0.35

Total Time - Full LMM Model with Random Intercepts - Skilled Deaf Readers

	b	***SE***	***t-value***
Frequency	5.09	9.41	0.54
Predictability	14.65	9.41	1.56

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Total Time - Full LMM Model with Random Intercepts - Skilled Deaf Readers			
	b	***SE***	***t-value***
Frequency × Predictability	4.22	18.79	0.22

Total Time - Full LMM Model with Random Intercepts – Less-skilled Deaf Readers			
	b	***SE***	***t-value***
Frequency	7.50	11.16	0.67
Predictability	51.00	11.16	4.57
Frequency × Predictability	11.69	22.30	0.52

Probability of Regressions In - Full LMM Model with Random Intercepts				
	b	***SE***	***z-value***	***p-value***
Group SKH-SKD	−0.14	0.38	−0.37	0.71
Group SKD-LSKD	−0.11	0.38	−0.30	0.77
Frequency	−0.35	0.16	−2.20	0.03
Predictability	0.22	0.16	1.36	0.17
Group SKH-SKD × Frequency	0.14	0.33	0.42	0.68
Group SKD-LSKD × Frequency	0.10	0.33	0.29	0.77
Group SKH-SKD × Predictability	−0.47	0.33	−1.40	0.16
Group SKD-LSKD × Predictability	0.90	0.33	2.70	0.01
Frequency × Predictability	0.20	0.32	0.62	0.54
Group SKH-SKD × Frequency × Predictability	−0.30	0.66	−0.46	0.65
Group SKD-LSKD × Frequency × Predictability	0.93	0.67	1.40	0.16

Probability of Regressions In - Full LMM Model with Random Intercepts – Skilled Deaf Readers				
	b	***SE***	***z-value***	***p-value***
Frequency	−0.34	0.27	−1.27	0.21
Predictability	−0.22	0.27	−0.82	0.41
Frequency × Predictability	−0.25	0.53	−0.48	0.63

Probability of Regressions In - Full LMM Model with Random Intercepts – Less-skilled Deaf Readers				
	b	***SE***	***z-value***	***p-value***
Frequency	−0.24	0.22	−1.10	0.27
Predictability	0.64	0.22	2.87	0.004

Probability of Regressions In - Full LMM Model with Random Intercepts – Less-skilled Deaf Readers

	b	***SE***	***z-value***	***p-value***
Frequency × Predictability	0.66	0.44	1.49	0.14

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Table 1

Example of sentences used in the experiment. Target words are in italics.

	Stimuli
High Frequency Target – Neutral Context	Frank watched a movie with his cute *baby* every single night.
High Frequency Target – Predictable Context	The new dad took care of his crying *baby* every single night.
Low Frequency Target – Neutral Context	Katherine likes to watch the tall *zebra* run around in the big cage.
High Frequency Target – Predictable Context	At the zoo, Jane saw the tall black and white *zebra* run around in the big cage.

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Table 2

Participant means for eye movement measures.

	High Frequency Targets		Low Frequency Targets	
First Fixation	**Predictable**	**Neutral**	**Predictable**	**Neutral**
SKH	201	207	205	217
SKD	207	213	206	219
LSKD	223	236	230	249
Gaze Duration				
SKH	229	236	230	248
SKD	220	226	227	247
LSKD	255	286	262	296
Total Time				
SKH	256	278	251	277
SKD	256	270	260	276
LSKD	305	350	305	358
Skipping Probability				
SKH	0.22	0.16	0.16	0.12
SKD	0.23	0.18	0.21	0.15
LSKD	0.20	0.13	0.18	0.10
Regressions In				
SKH	0.10	0.12	0.06	0.08
SKD	0.11	0.10	0.09	0.07
LSKD	0.09	0.11	0.06	0.12