INVESTIGATING VISUAL DEGRADATION COSTS IN WORD RECOGNITION

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Abstract

Skilled reading is an outcome of perceptual expertise. Years of practice shift perceptual processing from a serial to a parallel analysis of a word's components (e.g., letters). Degrading a word by letter spacing or word inversion (i.e., 180° rotation) impairs recognition, possibly because a fast parallel-process fails and the reader resorts to a slow serial-process (Cohen et al., 2008). To examine this proposal we manipulated the mode of visual degradation (inversion, spacing, or both), word length (3-6 letters) and stimulus duration (limited, unlimited) in a semantic decision task. The main finding was that a word length effect (WLE), marking the transition from parallel-to-serial analysis, emerged in response times for words degraded by inversion that were presented for an unlimited duration, but was absent for inverted words presented for a limited duration (174 ms).This finding supports the view of two successive perceptual processing stages – parallel and serial - during word recognition (e.g., Ans et al., 1998). However, an unexpected difference between 5- and 6-letter standard words in the unlimited duration warrants modification of such a "2-stage" model. We discuss the addition of a "verification" process to resolve these seemingly contradictory findings.

Reading is a complex activity that relies on perceptual, linguistic and cognitive processes. Beginning readers are slow and make many errors during reading. One characteristic of young readers is the dependence of reading rate on the number of letters in the word. This word length effect (WLE) disappears when a child transitions from a beginner to a skilled reader (Martens & de Jong, 2006). For instance, Acha & Perea (2008) observed a WLE in a lexical decision task for beginning and intermediate readers across all items, whereas for adult readers this effect was present only for nonword items. Martens & de Jong (2006) investigated WLE in dyslexia using a lexical decision task. They observed a WLE for words and nonwords in the dyslexic children and their reading-age (2^{nd} grade) control group, but the effect was present only for nonwords in the chronological-age (4^{th} grade) control group.

In skilled readers, the absence of a WLE for familiar words is thought to reflect a shift from slow serial grapho-phonemic recoding to fast parallel orthographic processing and activation of phonology (Acha & Perea, 2008; Alario, De Cara, & Ziegler, 2007; Cohen, Dehaene, Vinckier, Jobert, & Montavont 2008; Martens & de Jong, 2006). It is possible to induce a WLE in adult readers by perceptually changing the word from its standard format to a less familiar format using MiXeD case (Lavidor & Eillis, 2001) or angular rotation (Koriat & Norman, 1985). The impact of angular rotation on word recognition has been known for over three decades. For instance, Koriat & Norman (1985) presented items at various rotations for an unlimited duration within the context of a lexical decision task. They found a WLE in adults for both words and nonwords that were rotated beyond a 60^{o} angle. This finding was interpreted as evidence for a "piecemeal" cognitive mechanism that restores the components of the word (e.g., letters) to their standard orientation before word recognition proceeds. In a recent fMRI study, Cohen et al. (2008) investigated the cost of visual degradation to word recognition by presenting words for a relatively short duration (170 ms) and degrading them by either angular rotation (from 0^{o} to 90^{o}), blank spaces between letters, or displacement in the visual field. This study found that above certain degradation levels the ability to make a semantic decision deteriorated and a WLE emerged in the decision latencies. The appearance of a WLE coincided with an increase in neural activity in the dorsal visual pathway, which was attributed to the deployment of attention required for a serial analysis of visually degraded words. Taken together, behavioral and imaging findings suggest that a WLE marks the transition from parallel-to-serial analysis during word recognition.

To explain processing differences among familiar and less familiar words, Ans, Carbonnel, & Valdois (1998) proposed a theoretical "2-stage" model of word recognition. According to this model there are two successive and different processing stages in word recognition, a global and an analytic stage. The global process always occurs first, however, when the item is not recognized by the reading system a second analytic process is carried out. During the analytic stage the largest initial recognized component of the letter string is processed first, and then processing continues to the next component until the end of the item. When a word is visually degraded it is less familiar, therefore, the global (i.e., parallel-processing) stage fails and the analytic (i.e., serial-processing) stage is executed (Cohen et al., 2008). In the current study we degraded familiar words to explore the emergence of a WLE in skilled readers during a semantic decision task. Mode of visual degradation was manipulated by inverting words, spacing letters, and presenting stimuli for a limited duration. Based on the 2-stage model (Ans et al., 1998), we hypothesized that a WLE would emerge for the visually degraded items (i.e., inverted and\or spaced words); and the size of this effect would be larger when stimulus duration is unlimited, relative to a limited duration, because then the second analytic stage would have enough time to complete.

Method

Participants

Fifty-three undergraduates from the Open University of Israel took part in the experiment as part of a course requirement (M±SD; 26.11±5.22 years; 47 women). The participants were native Hebrew speakers, had normal or corrected-to-normal vision, and did not report impairments in learning or reading.

Experimental Design and Stimuli

Participants performed a semantic decision task, in which they responded with a yes/no button press to the question: "Is the item a name of an animal?" Three independent variables were manipulated within-subjects: display orientation (0° rotation - “standard display” vs. 180° angular in-plane rotation - “inverted display”), letter spacing (the number of blank spaces

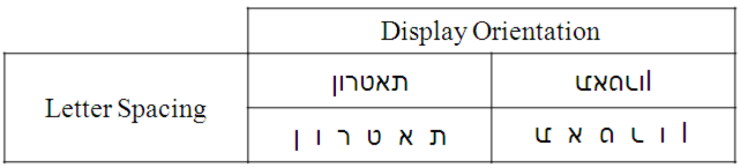

Figure 1. Four modes of visual degradation: standard (top left), inverted (top right), spaced (bottom left), inverted and spaced (bottom right).

between letters, 0 vs. 2 spaces), and word length (3-, 4-, 5-, and 6-letters). Stimuli were presented in 4 blocks, corresponding to a 2 (display orientation) × 2 (letter spacing) matrix of visual degradation mode (Figure 1). The duration of the stimuli (limited - 174 ms or unlimited) was manipulated between-subjects.

One hundred and sixty word-items were pseudorandomly assigned to 4 lists, which were associated with a degradation mode in a counterbalanced manner across participants. Stimuli were presented randomly within each experimental block. Each list consisted of 40 words, 10 items in each string length (3-6 letters). The average subjective written frequency of the word-items was matched across lists and word lengths, using subjective frequency measures on a 1-7 point scale provided by *the word-frequency database for printed Hebrew* (Frost & Plaut, 2005). There were no significant differences among the lists (M±SD; list 1: 4.24±.73; list 2: 4.28±.77; list 3: 4.22±.88; list 4: 4.22±.76; $F(3,144) = .05$, $p > 1$); the word lengths [$F(3,144) = .045$, $p > 1$]; and the list by word-length interaction [$F(9,144) = .085$, $p > 1$]. The 160 word stimuli did not refer to a name or a part of an animal. To ensure constant attention during the task, 4 additional sets of 12 names of animals (a total of 48 animal-targets) were included as infrequent targets for the semantic decision task. The length of the target items corresponded to that of the word items. Thus, each list consisted of 10 words and 3 animal-targets at each length (a total of 52 items per list).

Stimuli were presented in Ariel font size 18, black on a white background, at the center of the screen. The participant sat approximately 60 cm from the screen. In the typical spacing condition, the stimuli subtended from 1.7° to 3.5° of visual angle in width, and 0.7° of visual angle in height. In the 2-letter spacing condition, stimulus width was from 2.7° to 6° of visual angle, with a height of 0.7° visual angle.

Procedure and Apparatus

The participants were tested individually in a dimly lit room and were randomly assigned to a stimulus duration condition. They were presented with 4 separate blocks of stimuli corresponding to the 4 modes of visual degradation (see Figure 1). Block order was randomly determined for each participant. In the beginning of each block, the participant was informed of the mode of degradation. In the limited duration condition, each trial began with a 400 ms fixation dot in the center of the screen, followed by a 300 ms blank screen, next the stimulus appeared for 174 ms, and was replaced by a 2126 ms fixation dot. The participant could respond any time after the stimulus appeared and until the second fixation dot was terminated. In the unlimited duration condition, each trial began with a 500 ms fixation dot, followed by a 500 ms blank screen, and then the stimulus appeared until the participant responded with a button press. Six practice trials were given prior to the experiment, demonstrating the different modes of degradation relative to the standard format. The stimuli in the practice trials were 4 words and 2 animal-targets that were not used in the experiment.

Stimulus presentation and response measurement were governed by E-Prime 2.0 software (Psychology Software Tools, Inc., Pittsburgh, PA). The stimuli were generated by a Dell Pentium computer attached to a LG 17 inch color monitor (with a 85 Hz refresh rate, set to a resolution of 1024 × 768 pixels). Button press responses were collected via a Serial Response Box (Modal 200A, Psychology Software Tools).

Results and Discussion

Four participates were excluded from the final analysis, because their average RT in the standard display (collapsing across letter spacing and word length) was more than 2.5 SD from the mean of their duration group. Hence, data from 48 (M±SD; 26.22±5.41 years, 43 female) participants were included in the final analysis. The mean age of the participants in the duration groups did not differ significantly [$t(46) = -.18$, $p > .1$].

In the following analyses, Reaction time (RT) and accuracy data for the word-item trials only was used as the dependent measures. Trials with RTs smaller than 250 ms were removed from the analysis (.071% of trials). For each participant, the mean RT for the correct response trials and the overall mean accuracy were computed. The data was analyzed by subjects using a (2) × (2) × (4) × 2 repeated measures ANOVA, with display orientation (standard vs. inverted display), letter spacing (0 vs. 2 spaces), and word length (3-, 4-, 5-, and 6-letters) as within-subjects variables, and stimulus duration (limited or unlimited) as a between-subject variable. Effect sizes were computed using partial eta squared (η^2_p), which denotes the proportion of total variability attributable to an independent variable. Table 1 shows the mean RTs and accuracy for each duration group across all of the conditions.

Response Times

The ANOVA revealed significant main effects of display orientation [$F(1,46) = 135.58$, $p < .01$, $\eta^2_p = .74$] and word length [$F(3,138) = 41.84$, $p < .01$, $\eta^2_p = .47$]. Consistent with previous findings (Koriat & Norman, 1985; Cohen et al., 2008), RTs were slower for inverted relative to standard words and for longer relative to shorter words (i.e., a WLE). We also found a significant main effect of stimulus duration [$F(1,46) = 37.28$, $p < .01$, $\eta^2_p = .44$], with shorter RTs for the limited as compared to the unlimited condition. In contrast to Cohen et al. (2008), we did not detect an effect for letter spacing, possibly because spacing is less detrimental to the recognition of unpointed Hebrew words that are represented mainly by consonantal letters, as compared to French words that consist of both consonant and vowel letters. The following 2-way interactions were significant: display orientation × stimulus duration [$F(1,46) = 17.95$, $p < .01$, $\eta^2_p = .28$], word length × stimulus duration [$F(3,138) = 22.59$, $p < .01$, $\eta^2_p = 0.32$], and display orientation × word length [$F(3,138) = 35.59$, $p < .01$, $\eta^2_p = .43$]. Figure 2 shows the significant 3-way interaction among display orientation × word length × stimulus duration [$F(3,138) = 23.26$, $p < .01$, $\eta^2_p = .33$]. Planned comparisons using the Bonferroni test showed that in the unlimited stimulus duration there was a significant increase

Table 1. Mean RTs and accuracy for the experimental conditions. SD denoted in parentheses.

Stimulus duration	Word length	RT (ms) Standard	RT (ms) Standard spaced	RT (ms) Inverted	RT (ms) Inverted spaced	Accuracy (%) Standard	Accuracy (%) Standard spaced	Accuracy (%) Inverted	Accuracy (%) Inverted spaced
Limited	3 letters	421.57 (74.53)	425.12 (83.93)	627.82 (207.95)	633.80 (172.34)	78.33 (28.38)	78.33 (26.32)	83.33 (15.51)	89.58 (15.17)
	4 letters	417.31 (85.39)	436.32 (79.91)	624.42 (188.05)	655.78 (149.58)	77.08 (25.44)	83.75 (20.81)	83.33 (16.85)	83.75 (15.82)
	5 letters	433.50 (101.61)	426.67 (89.57)	697.78 (227.98)	677.43 (189.91)	73.75 (28.10)	81.25 (23.64)	83.33 (18.33)	86.25 (16.10)
	6 letters	418.21 (82.23)	455.54 (87.17)	638.54 (206.53)	682.32 (227.59)	77.50 (24.18)	83.33 (21.19)	75 (22.26)	85.41 (13.18)
Unlimited	3 letters	551.73 (81.25)	588.78 (137.31)	900.77 (272.66)	894.27 (243.51)	100 (0.00)	100 (0.00)	100 (0.00)	100 (0.00)
	4 letters	562.90 (115.28)	583.18 (122.14)	992.88 (312.01)	1004.10 (299.61)	100 (0.00)	99.58 (2.04)	99.16 (2.82)	99.58 (2.04)
	5 letters	547.13 (116.24)	542 (82.01)	1075.39 (335.54)	1131.74 (368.62)	99.58 (2.04)	100 (0.00)	98.75 (4.48)	100 (0.00)
	6 letters	561.49 (98.02)	605.36 (122.03)	1206.49 (462.65)	1204.50 (377.92)	98.75 (4.48)	99.16 (2.82)	98.75 (3.37)	98.75 (3.37)

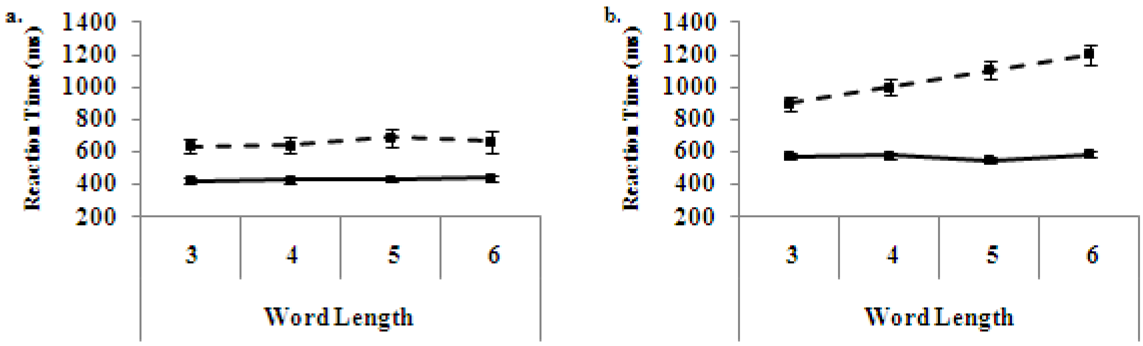

Figure 2. Mean RT for display orientation × word length in the (a) limited and (b) unlimited stimulus duration groups. Dashed lines denote inverted display and solid lines denote standard display. Bars denote 1 standard error of the mean.

in RT for inverted words as word length increased (i.e., a WLE). This difference was significant among all word lengths (all $p < .01$). Furthermore, in the unlimited duration the RT for standard words was significantly different among 5- and 6-letter stimuli ($p < .05$).

Considering the 3-way interaction, our results are incompatible with those of Cohen et al (2008). We presented words for both a limited (174 ms) and an unlimited duration, observing WLE only in the latter condition. Cohen et al. (2008), on the other hand, presented words only for 170 ms and found a WLE in this duration. One explanation for these discrepant results is that they used a maximum angular rotation of 90^o, whereas we displayed words at 180^o rotation. Previous findings have shown that 180^o rotation is perceptually more similar to a standard word (0^o rotation) and thus elicits faster RTs (Koriat & Norman, 1985).

Accuracy

Table 1 shows the mean accuracy for each duration group across all of the conditions. The ANOVA showed a significant main effect of letter spacing [$F(1,46) = 4.27$, $p < .05$, $\eta^2_p = .08$], with higher accuracy for 2-spaces relative to 0-spaces. This finding contradicts the hypothesis that any mode of visual degradation would impair word recognition, because spacing improved decision accuracy. The view that a "piecemeal" mechanism corrects degraded words (Koriat & Norman, 1985) could explain this finding, because such a mechanism overcomes degradation by encoding smaller-units of an item. Spacing increases the saliency of a word's components, which would, therefore, assist a piecemeal mechanism. There was also a significant main effect of stimulus duration [$F(1,46) = 41.4$, $p < .01$, $\eta^2_p = .47$], with higher accuracy for the unlimited duration condition. This finding implies that in the limited condition the semantic decision was based on a coarse-grain perceptual representation, because a verification process did not have enough time to complete (see Conclusions). In addition, the following interactions were significant, however their effect sizes were small: display orientation × word length [$F(3,138) = 3.37$, $p < .05$, $\eta^2_p = .06$], display orientation × word length × stimulus duration [$F(3,138) = 3.23$, $p < .05$, $\eta^2_p = .06$], and display orientation × letter spacing × word length × stimulus duration was marginally significant [$F(3,138) = 2.59$, $p = .055$, $\eta^2_p = .05$].

Conclusions

Cohen et al. (2008) reported a WLE when visually degraded words were displayed for a limited duration. In our study, a WLE was not found using similar modes of degradation and stimulus duration, possibly because our level of degradation was less severe as indicated by participants' performance. When stimulus duration was unlimited, however, a WLE emerged for both inverted and standard words. The presence of a WLE for inverted words in this condition suggests that when processing time is not constrained additional processes can occur, such as those proposed by Ans et al. (1998) 2-stage model of word recognition. A potential challenge for this model is our finding of a length effect between 5- and 6-letter standard words in the unlimited duration. According to this model, these words were familiar and displayed in a standard orientation, therefore, the parallel-process should have sufficed for recognition. But the presence of a length effect suggests that an additional serial-process took place. To account for this pattern of findings we propose that a verification process occurs post-encoding (akin to the process proposed by Paap, Newsome, McDonald, & Schvaneveldt, 1982); in which a lexical representation, activated by the outcome of a parallel-processing stage, is compared to a fine-grain perceptual representation, which is the outcome of a serial-processing stage. This verification can be triggered by degraded stimuli, limited processing time or a large quantity of information. Such a verification process may be important for beginning readers because it would allow them to evaluate whether their initial encoding of the word was accurate.

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