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Reading sideways: Effects of egocentric and environmental orientation in a lexical decision task

Nicolas Davidenko[a,*], Alexander Ambard[b]

[a] Psychology Department, University of California, Santa Cruz, CA, USA
[b] Google, Inc., Mountain View, CA, USA

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ABSTRACT

Many image-level factors affect reading speed and comprehension, including the in-plane orientation of text. As words' angular deviation from upright increases, so do response times. Here we investigated whether these orientation effects in reading are based purely on an egocentric (retinal) reference frame, or whether there is also a contribution of the environmental reference frame. Participants completed a lexical decision task with six-letter, two-syllable words and nonwords presented at a wide range of angles, in increments of 22.5°. A control group of participants (N = 66) completed the task while sitting upright, and an experimental group (N = 43) completed the task while lying sideways on their right side. The function relating the egocentric orientation of strings to response times was symmetric for upright observers, but skewed for observers who lay sideways, with an advantage for responding to environmentally upright text. Our results suggest that sideways readers may use an oblique reference frame (similar to the perceptual upright) for mentally rotating text. We discuss implications for designing optimal text orientations in head mounted displays.

1. Introduction

Decades of research on reading reveal a number of image-level factors affect reading speed and comprehension. For example, the font (Jolicoeur, Snow, & Murray, 1987), the spacing between characters (Legge, Rubin, Pelli, & Schleske, 1985), and the spatial frequency and contrast of the words (Lovegrove, Bowling, Badcock, & Blackwood, 1980), and the position of text relative to fixation (Rayner, Well, Pollatsek, & Bertera, 1982) all influence reading speed and comprehension. Understanding how these factors affect reading can help to create more readable displays and teaching materials, which may benefit individuals with dyslexia and other reading impairments. One factor that has a profound impact on reading is the in-plane orientation of text.

Miles Tinker (1956) conducted one of the earliest studies on the role of in-plane orientation in reading. He presented observers with 30-word paragraphs that were either upright or rotated by ± 45° or ± 90° and instructed them to read each passage to identify a word that "spoils its meaning." The effect of rotation on this high-level reading task manifested as substantially slower reading times as text deviated from upright: a ± 45° rotation increased reading times by 50%, while a ± 90° rotation increased reading times by over 200%. Tinker argued that several factors could lead to this lag, including (1) the lack of exposure to misoriented letters, (2) the lack of eye muscle practice making oblique or vertical eye movements during reading, and (3) the impairment of whole word processing that normally relies on a horizontal arrangement of letters and a right visual hemifield advantage (see Rayner et al., 1982). When words are obliquely or vertically rotated, observers cannot take advantage of this holistic strategy and must resort to more piece-meal reading. Interestingly, Tinker (1956) did not find any asymmetries in reading time between clockwise (CW) and counter-clockwise (CCW) text rotations, at either 45° or 90°, leading him to conclude that backbone titles on books may be read equally well (or poorly) from top to bottom as from bottom to top.

It was not until the 1980s that researchers began to focus more closely how in-plane orientation affects reading at the level of single characters and words. Studies by Jolicoeur and Landau (1984) were among the first to show that rotating characters impacts recognition. Whereas earlier studies (e.g. Corballis, Zbrodoff, Shetzer, & Butler, 1978; Simion, Bagnara, Roncato, & Umilta, 1982) had found no effect of orientation on latencies or performance in letter recognition tasks, Jolicoeur and Landau (1984) used a more sensitive measure by examining error rates following very brief (~25 ms) presentations. Their studies revealed performance costs with rotations as small as 30° that grew linearly until 180°. They concluded that letter recognition does indeed depend on the angle of presentation, but the speed of "mentally

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* Corresponding author at: 1156 High Street, Social Sciences 2, Santa Cruz, CA 95064, USA.
E-mail address: ndaviden@ucsc.edu (N. Davidenko).

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rotating" single letters (which they estimated to be 12°/ms, or 180° in 15 ms) is too fast to be detected in typical experiments where characters remain on the screen indefinitely.

Following this work, Koriat and Norman (1984, 1985) conducted a series of studies on the role of orientation in word and single character recognition in Hebrew. Koriat and Norman (1984) presented native Hebrew speakers with 5-letter words and nonwords (modified by one letter) at 0°, ± 60°, ± 120°, and 180°. They found that response times to correctly identify words increased as a function of angular deviation from upright, but this increase was not linear. Words at ± 60° took 26% longer to identify than upright words, but words at ± 120° took around 140% longer than upright words, with no additional delay for 180° words. In follow-up work, Koriat and Norman (1985) examined this effect for 3-, 4- and 5-letter words and found an interaction between orientation and word length: longer words led to larger costs of rotation than shorter words. In addition, they replicated the non-linear pattern of latencies found in their previous study, and suggested that there are three different orientation "regions" for word recognition. In the first region (between 0° and ± 45°) response times are practically insensitive to orientation or word length. In the second region (between ± 60° and ± 120°), orientation effects grow sharply and depend on word length. In the third region (between ± 120° and 180°), latencies reach a plateau and are no longer sensitive to word length. Babkoff, Faust, and Lavidor (1997) later corroborated these finding in a lexical decision task in which native Hebrew speakers observed 3- and 5-letter Hebrew words at 0°, 15°, 30°, 45°, 60°, or 90°. The authors found that response times to correctly identify words was relatively constant for angles between 0° and 60°; however, there was a sharp increase in response times between 60° and 90°.

The nonlinear relationship between orientation and latencies suggests that reading rotated words does not simply involve mental rotation, which would otherwise lead to response times that increase linearly with angular deviation from upright (Shepard & Metzler, 1971). Instead, reading rotated words may involve (at least) two separate processes: (1) the mental rotation of single characters, which increases linearly with angular deviation and (2) the assembling of the rotated characters into a whole word, which can happen at a glance (i.e. holistically) for small angular deviations, or must happen in a piece-meal way for larger angular deviations.

Although such a two-process theory appears to explain the pattern of latencies when words are rotated relative to an upright observer, it leaves open the question of what reference frame(s) these processes rely on. The majority of research on reading has been done with participants sitting upright in front of an upright monitor, in an upright experiment room, etc., wherein many internal and external references are aligned. However, a large body of research in the recognition of shapes (Rock, 1956), judgments of orientation (Dyde, Jenkin, & Harris, 2006), biological motion (Troje, 2003; Chang, Harris, & Troje, 2010), face perception (Davidenko & Flusberg, 2012), and clock reading (Davidenko et al., 2018) has shown that extra-retinal references play a significant role in orientation-dependent visual processing. When observers tilt their heads and/or bodies, both egocentric (i.e. head-centered) and environmental (i.e. world-centered) reference frames influence performance and response time. For example, when observers lie sideways at 90° they perform better and faster at a face expression recognition task when faces are presented upright (relative to gravity) compared to upside down (Davidenko & Flusberg, 2012). This advantage in processing environmentally upright faces remains after accounting for a small (~4°) compensatory ocular counter-roll (OCR), physiological response that rotates the eyes of tilted observers several degrees toward the environmental upright (see Bischof & Scheerer, 1970).

Environmental reference frames are known to affect both low level and high level visual processing; however, there is very little research on the role of environmental reference frames in reading. In one of the few studies examining reading under different head angles, Firth, Machin, and Watkins (2007) used the Wilkins Rate of Reading Test (Wilkins, Jeanes, Pumfrey, & Laskier, 1996) to examine the effect of tilting text versus tilting the head of the reader. From their results, they concluded that the major factor determining reading speed was the mismatch between the orientation of the text and that of the reader, thus attributing orientation effects in reading entirely to an egocentric reference frame. However, the set of conditions they tested (head and body tilts of 15° or 30°, 45° and 90°, with text presented at either 0° or 90°, was not optimally chosen to detect a contribution of external reference frames. Specifically, Firth et al. (2007) did not test whether 90° participants were faster to read environmentally upright compared to environmentally inverted text. If there is an effect of the external environment on reading, it would manifest most clearly across those two conditions.

In the present studies, we examined whether the environmental reference frame (cued by vestibular, tactile, proprioceptive, and visual cues) contribute to reading speed. To test this, we designed a lexical decision task using 192 six-letter, two-syllable English words (and 192 matched nonwords) at a wide range of egocentric angles, while participants either sat upright or lay sideways. If orientation effects in word reading are based purely on an egocentric reference frame, latency patterns should follow a curvilinear function of the egocentric orientation of words, and there should be no difference in the pattern of latencies as a function of the observer's body position. However, if the environmental reference frame does play a role, participants lying sideways should respond faster to environmentally upright words than to environmentally inverted words.

2. Methods

2.1. Participants

Participants were 109 University of California, Santa Cruz undergraduate students (68 female, 35 male, 2 non-binary, 4 unknown; ages 18–27) who gave informed consent and completed the experiment for Psychology course credit. All were right-handed and had normal or corrected vision. Due to convenience sampling, an unequal number of participants were assigned to the two conditions: 66 participants were assigned to the control group (sitting upright) and 43 to the experimental group (lying on their right side). The experimental procedures were approved by the UCSC Institutional Review Board, and were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Stimuli

We selected 192 six-letter, two-syllable, medium-frequency English words from a TV and movie transcript database (Wiktionary, 2006). Frequencies of the 192 words ranged from 44 to 91 based on the 29,213,800-word database. For each word, we generated a matched nonword by permuting its two syllables and making additional letter permutations as necessary to create a pronounceable nonword. The complete list of words, nonwords, and the frequency and rank of words within the database are provided in Appendix A. Stimuli were presented on an upright 15-inch laptop that was positioned 18 in. (45.7 cm) from the participant. Strings were shown in black, bolded Helvetica font in the center of a gray screen, subtending approximately 1.8° × 6° of visual angle. The first letter of each string was capitalized to facilitate the process of determining the correct direction in which to read each string.

2.3. Procedure

Each trial began with a brief presentation of a fixation cross followed by a presentation of a word or nonword centered horizontally and vertically on the point where the fixation cross had been. The string remained on the screen, until the participant responded by pressing 1 to