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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

* 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 indicate that the string was a word, or 2 to indicate that it was a nonword. After the response, a brief (200 ms) blank screen was shown, and the next trial began. No feedback was given. Words and nonwords were presented in fixed-orientation blocks at 16 different egocentric orientations: 0°, ± 22.5°, ± 45°, ± 67.5°, ± 90°, ± 112.5°, ± 135°, ± 157.5°, ± 180°, with 12 words and 12 nonwords presented at each orientation in a pseudorandom order. Trials were blocked by orientation, the order of which was randomized across participants. No strings were ever repeated throughout the experiment, as repetition is known to greatly reduce effects of orientation on reading speed (Jordan & Huntsman, 1990). The assignment of specific strings to specific angles was also randomized for each participant. The task took approximately 15 min to complete. Critically, a control group of participants (N = 66) performed the lexical decision task while sitting upright, and an experimental group (N = 43) performed the task while lying sideways on their right side.

2.4. Control group: sitting upright (N = 66)

The control group performed the task while sitting upright. Participants were instructed to rest their head on a chin rest and resist any urge to move or tilting their head for the duration of the experiment. A research assistant stayed in room ensuring participants did not move their head throughout the experiment. Participants entered their responses on a number pad, with their index and middle fingers positioned on the 1 and 2, respectively.

2.5. Experimental group: lying sideways (N = 43)

The experimental group did the same task while lying sideways on their right side. A research assistant helped position the participant's head horizontally on a contoured pillow until their eyes were vertically displaced, and instructed the participant to avoid moving their head for the duration of the experiment. The laptop on which stimuli were presented was positioned upright on an height-adjustable chair, such that the center of the screen was directly in front of the participants' eyes. Participants held the number pad on their left hand, with their index and middle fingers positioned on the 1 and 2, respectively.

3. Results

3.1. Control group results

A 2-way repeated measures ANOVA on performance with factors of orientation (16) and word/nonword (2) revealed a main effect of string orientation on performance ($F(15,2015) = 21.4$, $p < 0.0001$), but no main effect of word/nonword ($F(1,2015) = 0.003$, $p = 0.96$) and no interaction ($F(15,2015) = 0.631$, $p = 0.85$). Performance on the lexical decision task was high and practically constant for string orientations between −90° (CW) and +90° (CCW), with mean performance on words and nonwords ranging from 0.934 to 0.977 across that range of angles. Performance gradually decreased for larger angular deviations, with the lowest performance at 0.833 for words rotated by 180°. Because performance was relatively high across the entire range of text orientations, we focus the remainder of our analyses on response times on correct trials.

We computed the average reaction time (RT) on correct trials for each subject based on their median RT at each word or nonword orientation, thus eliminating the contribution of outlier RTs. Across subjects, we computed the mean and standard error based on these subject-wise median RTs. A 2-way repeated measures ANOVA on correct response times with factors of orientation (16) and word/nonword (2) revealed a significant main effect of string orientation ($F(15,2015) = 10.34$, $p < 0.0001$), a significant main effect of word/nonword ($F(1,2015) = 14.54$, $p < 0.0001$), and a significant interaction ($F(15,2015) = 3.277$, $p < 0.0001$). Correct response times to

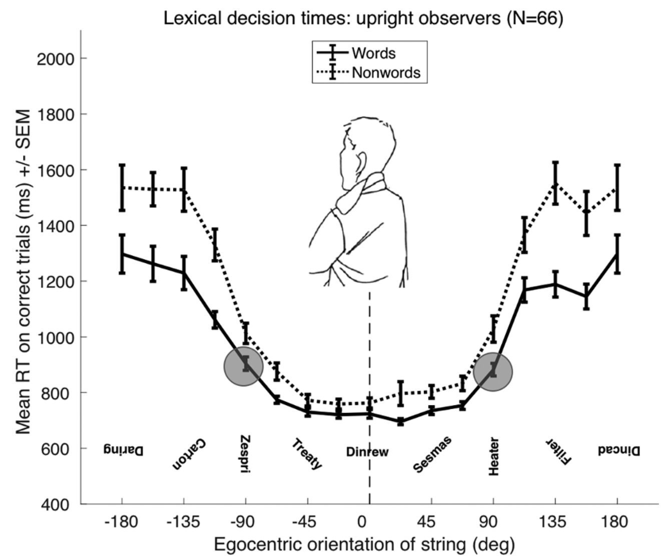

Fig. 1. Mean response times (RTs) on correct trials in a lexical decision task across participants in the control group (sitting upright) for egocentric angular deviations from −180° (CW) and 180° (CCW) in steps of 22.5° (note: data at −180° and 180° are the same and shown for symmetry of the visualization). Solid line shows mean RTs for words and dotted line for nonwords. Error bars indicate standard error of the mean across 66 observers. The data points highlighted in gray discs represent response times for words rotated by 90° CW (left) and 90° CCW (right), which did not differ from each other.

nonwords were longer than to words, a difference that increased with angular deviation. At the upright orientation, correct responses to nonwords took on average 763 ms, while correct responses to words took 724 ms (difference: 39 ms, paired *t*-test: $t(65) = 2.82$, $p = 0.006$). Meanwhile, at 180°, observers took 1535 s to respond to nonwords, compared to 1297 ms for words (difference: 238 ms, $t(65) = 5.04$, $p < 0.0001$). The RT cost for responding to nonwords vs. words was significantly larger at 180° than at 0° ($t(65) = 5.33$, $p < 0.0001$).

Beyond the difference in RTs between words and nonwords, there was a very large effect of orientation on RTs for both types of strings (see Fig. 1). Replicating previous findings, the function relating angular deviation and response time was nonlinear, and could be described in terms of Koriat and Norman's (1985) three "regions." Response times were short and relatively stable for angular deviations between −67.5° (CW) and +67.5° (CCW). There was a sharp increase in response times between ± 90° and ± 135°, and then they leveled off between ± 135° and 180°.

Notably, the effects of orientation were symmetric across CW and CCW orientations. A 2-way repeated measures ANOVA with factors of absolute angular deviation from upright (7 levels: 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°) and direction (2 levels: CW vs. CCW) showed a main effect of absolute angular deviation from upright ($F(6,923) = 96.7$, $p < 0.00001$), and an interaction between absolute angular deviation and direction ($F(6,923) = 7.6$, $p < 0.00001$), but no main effect of direction ($F(1,923) = 2.4$, $p = 0.12$). In particular, there was no difference in response times to identify words at −90° (CW; 721 ms) compared to +90° (CCW; 696 ms; $t(65) = 1.07$, $p = 0.29$).

3.2. Experimental group results

We analyzed results in the experimental group in the same way as in the control group, considering the *egocentric* angle of the strings as a predictor of response time on correct trials. A 2-way repeated measures ANOVA (factors: egocentric orientation (16) and word/nonword (2)) revealed a significant main effect of egocentric orientation on response times ($F(15,1302) = 11.41$, $p < 0.0001$), a significant main effect of word/nonword on response times ($F(1,1302) = 25.73$, $p < 0.0001$),

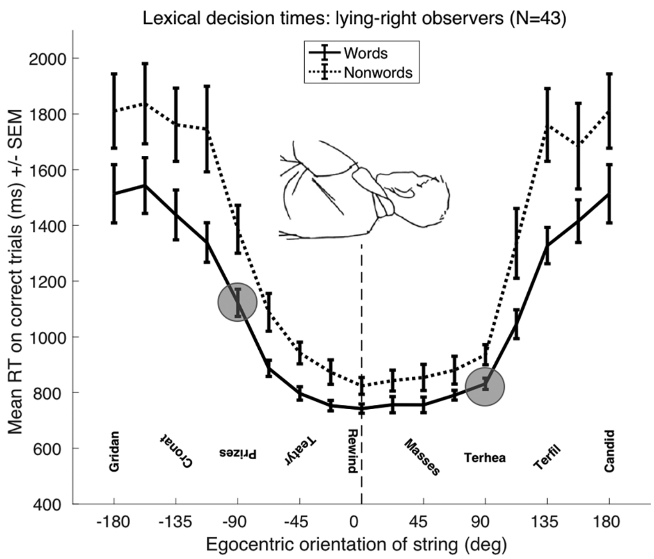

Fig. 2. Mean response times (RTs) on correct trials in a lexical decision task across participants in the experimental group (lying right) for egocentric angular deviations of the text. Solid line shows mean RTs for words and dotted line for nonwords. Error bars indicate standard error of the mean across 43 observers. The data points highlighted in gray discs represent response times for words rotated by 90° CW (left; environmentally inverted) and 90° CCW (right; environmentally upright), which differed significantly.

and no interaction ($F(15,1302) = 1.03$, $p = 0.42$). As in the control condition, response times to nonwords were longer than to words across all orientations.

Importantly, when participants were lying sideways, the effect of egocentric angle on correct response times was *asymmetric* across CW and CCW rotations (see Fig. 2). A 2-way repeated measures ANOVA with factors of absolute angular deviation from upright (7 levels: 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°) and direction (2 levels: CW vs. CCW) showed a main effect of absolute angular deviation from upright ($F(6,923) = 72.1$, $p < 0.000001$), a main effect of direction ($F(1,601) = 27.5$, $p < 0.000001$), and an interaction between absolute angular deviation and direction ($F(6,601) = 9.3$, $p < 0.00001$). The main effect of direction indicated that RTs were significantly faster for CCW rotations than CW rotations. Bonferroni-corrected paired t-tests (based on 7 planned comparisons, with significance level of 0.007) revealed significantly faster RTs to +90° words (CCW; environmentally upright; 832 ms) compared to −90° words (CW; environmentally inverted; 1122 ms; $t(42) = 7.03$, $p < 0.000001$); faster RTs to +67.5° words (791 ms) compared to −67.5° words (887 ms; $t(42) = 4.12$, $p = 0.0002$); and faster RTs to +112.5° words (1045 ms) compared to −112.5° words (1339 ms; $t(42) = 5.12$, $p = 0.0003$). In these cases, correct response times were shorter when the string was rotated CCW (i.e. toward the direction of environmental upright) compared to CW, a difference that was most striking when comparing latencies for +90° and 90° words.

We considered the possibility that a 90° body rotation causes a *phase shift* in the function that relates text orientation to response latency. Such a phase shift may correspond to participants mentally rotating words not to their retinal upright, but to their "perceptual upright" (see Dyde et al., 2006), which usually deviates by about 10°–15° from retinal upright toward the environmental upright for sideways observers. To quantify this phase shift across participants, we modeled each participant's correct response times to words as a sinusoidal function of egocentric orientation and determined the individual phase shifts that produced the highest correlation. For the control group (sitting upright), the best-fit sine curve was shifted by a mean of +1.2° (CCW), not significantly different than 0° ($t(65) = 1.0$, $p = 0.3$). In contrast, for the experimental group (lying right), the best-fit sine curve for was shifted by a mean of −11.6° (CW), significantly different than 0° ($t(42) = 9.43$, $p < 0.0001$). A two-sample *t*-test comparing the phase shifts for participants in the two groups reveals a large effect of body orientation ($t(107) = 8.3$, $p < 0.0001$), indicating that lying sideways introduces a reliable phase shift of in response times as a function of egocentric text orientation.

These results are consistent with the notion that when lying sideways, participants mentally rotate text toward a "perceptual upright" (see Dyde et al., 2006), which is a weighted combination of the egocentric (retinal) upright and the environmental upright. We note that the difference in mean phase shifts between in the two conditions (12.8°) is much larger than what would be predicted from ocular counter-roll, which we have previously measured in a similar paradigm to be around 4.5° (see Davidenko & Flusberg, 2012). This suggests that the contribution of the environmental reference frame cannot be accounted for by ocular counter-roll alone, and instead likely reflects a bias introduced by weighting environmental and egocentric reference frames.

4. Discussion

Our results replicate and extend previous findings that performance and response times in reading are affected by the in-plane orientation of words. By using a lexical decision task with six-letter, two-syllable English words and testing angular deviations at 22.5° increments, we extend previous findings on the role of text orientation in reading to an English speaking population. Importantly, by manipulating the observers' orientation across the control and experimental conditions, we identified a reliable influence of the environmental reference frame in response times to discriminate words from nonwords. Specifically, when lying sideways, participants were faster to classify strings that were rotated toward the environmental upright, compared to the environmental inverted. This result adds to a growing literature showing environmental reference frames affect high-level visual processing. Nevertheless, it is worth noting that the egocentric reference frame exerts a much larger influence than the environmental reference frame on response times. As such, when the two reference frames are pitted against one another, the egocentric reference frame would dominate the environmental reference frame. This may explain why previous work (Firth et al., 2007) found no effect of the environmental reference frame when they compared upright subjects reading tilted text with tilted subjects reading upright text. The most direct way to detect the influence of the environmental reference frame is to nullify the effect of egocentric orientation (by presenting words at egocentric +90° or −90°) and maximize the environmental orientation (by using environmentally upright and inverted text).

In previous work, Yu, Park, Gerold, and Legge (2010) provided evidence that the decrease in efficiency in reading vertically oriented text is correlated with visual span (the number of letters an observer can identify without making an eye movement), which is smaller along the vertical than horizontal meridian. Following up on this work, Yu, Legge, Wagoner, and Chung (2014) show that this effect is primarily due to visual crowding (as opposed reduced resolution in the periphery, or mislocation errors). In addition, by showing that the vertical impairment is more pronounced using a flashcard method (free reading of a sentence across four lines) compared to an RSVP method (foveated presentation of single words), the authors argued that impairments in reading vertically oriented text (whether it be rotated or marquee) are also likely influenced by difficulty planning and executing vertical eye movements during reading, processes that are more prevalent in the flashcard task. Finally, by using a non-letter control stimulus, the authors confirmed that the crowding asymmetry for vertical strings does not depend specifically on the use of letters, and occurs with upright letters, rotated letters, and even non-letter symbols. Because our lexical decision task used 6-letter, 2-syllable words and nonwords, presented at the fovea, our stimuli are likely to elicit more crowding when strings are egocentrically vertical than egocentrically horizontal. In fact, the data from Yu et al. (2010) suggest that a 6-letter word can be recognized at a glance (i.e. holistically) in a regular horizontal layout, but may require two fixations in a vertical layout. Thus, the effect of orientation in our task is likely driven by a crowding effect (more crowding along the egocentric vertical meridian) as well as a saccade effect (requiring an additional saccade for egocentrically vertical text). We note, however, that the contribution of eye movement and crowding to the RT cost for −90° and +90° rotated words cannot directly account for the asymmetry between CW and CCW rotations we found in our lying-right experiment. For example, it is not clear that an egocentrically downward saccade is more or less difficult to plan and execute than an egocentrically upward saccade, while lying sideways (but not so while lying upright). A future experiment comparing reading of short words vs. long paragraphs would help address the question of whether eye movements specifically contribute to our environmental effects.

Although our results indicate a robust effect of the environmental reference frame on reading speed, our experiment does not allow us to dissociate the potential sources of this effect. Since the laptop was always (environmentally) upright, and the room was kept lit throughout the experiment, participants had access to external visual (and nonvisual) cues as to the environment's orientation. Thus the effects of the environmental reference frame could arise through frame effects (e.g. the orientation of the laptop computer), other visual cues (the location of the floor, ceiling, and walls), tactile cues of the pillow pressing on one side of the face, as well as proprioceptive and vestibular cues. As such, we cannot isolate the potential sources of the environmental effects. However, in recent work (Davidenko et al., 2018) we have shown that both visual and non-visual cues contribute to environmental orientation effects in a clock-reading task by using Virtual Reality environments whose orientation could be dissociated from gravity. The results of that study suggest that the environmental 'phase shifts' are larger when the virtual and real environments are aligned.

Our results have implications for understanding reading in real-life reading scenarios when text does not appear upright. First we note that our lexical decision task differs in important ways from typical reading scenarios. In particular, determining whether a 6-letter string is a word or nonword can be accomplished with a single glance, or at most one saccade. In contrast, a realistic reading context involves the planning and execution of many forward and sweep eye movements. As others have argued (e.g. Essock, 1980) the impact of external reference frames in orientation-dependent processing seems to increase with the complexity of the visual task; as such we would predict that in a reading comprehension task that requires planning and executing eye movements, the orientation of text relative to the environmental upright would have an even more pronounced impact on performance and speed compared to our lexical decision task, and may manifest at smaller angles than in our lexical decision task. When a participant is lying sideways, reading environmentally upright or inverted text requires planning and executing (egocentrically) vertical eye movements, which are under-practiced as compared to more typical (egocentrically) horizontal eye movements. In this context, the observer might rely more on other contextual factors to facilitate the reading process, and one of those may be the alignment of text with the environmental frame of reference.

There are other real-life scenarios where the orientation of text can affect performance. For example, when people work together at a tabletop, they must arrange documents so as to minimize the angular deviation from upright for the multiple observers and shared displays (Mitchell, 2003; Wigdor & Balakrishnan, 2005). Our data corroborate previous findings in Hebrew (Koriat & Norman, 1985) that reading times for words increase in a nonlinear fashion as angular deviations increase, with a relatively shallow region between −60 and 60, a sharp ramp to 135, and a plateau through 180. However, these results change if one of the observers is not upright. When lying sideways, the sharp ramp starts sooner, at around 45°, for text rotations away from the environmental upright, but later, at around 90°, for text rotations toward the environmental upright.

Our findings are perhaps most relevant for situations where people are reading or interacting with text using a mobile or handheld display while lying sideways in bed or at an oblique angle on a couch. Most smart phones and tablets automatically rotate the display to remain (environmentally) upright once the orientation of the device passes a certain angular threshold relative to gravity. This makes it difficult to read while sideways if an observer's ideal text orientation is oblique (unless the auto-rotate feature is turned off). However, if the device could also sense the orientation of the user's head, it might adopt a different threshold orientation to rotate the display, leading to a better reading experience.

As the ubiquity of Virtual Reality, Augmented Reality, and the use of head-mounted devices (HMDs) continues to grow, we will encounter more situations that provide users the ability to engage with media while in non-upright positions (e.g. with one's head at an oblique angle on an airplane seat). Our findings suggest that an optimal orientation for presenting text when observers are lying sideways may not be exactly egocentric upright, but rather about 10°–15° away from egocentric upright, toward the environmental upright. It should be noted, however, that there was substantial variability across participants when we estimated individual phase shifts: for example, the standard deviation of phase shifts in the experimental condition was 9.6°, with some participants showing phase shifts as large as 30° while others showing phase shifts as small as 0°. Therefore, the "optimal" orientation to present text to non-upright observers will likely depend on the individual, and it may be best practice to let individual users determine their optimal screen orientation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2018.08.006.

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