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The influence of visual and vestibular orientation cues in a clock reading task

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ABSTRACT

We investigated how performance in the real-life perceptual task of analog clock reading is influenced by the clock's orientation with respect to egocentric, gravitational, and visual-environmental reference frames. In Experiment 1, we designed a simple clock-reading task and found that observers' reaction time to correctly tell the time depends systematically on the clock's orientation. In Experiment 2, we dissociated egocentric from environmental reference frames by having participants sit upright or lie sideways while performing the task. We found that both reference frames substantially contribute to response times in this task. In Experiment 3, we placed upright or rotated participants in an upright or rotated immersive virtual environment, which allowed us to further dissociate vestibular from visual cues to the environmental reference frame. We found evidence of environmental reference frame effects only when visual and vestibular cues were aligned. We discuss the implications for the design of remote and head-mounted displays.

1. Introduction

Our ability to process visual information is influenced by the motor and visual constraints of our embodied experience and our surrounding environment (Bridgeman, 1996). Our cognitive and neural representations of a visually presented object may change, for instance, depending on whether we intend to act upon the object or whether we are simply recognizing it for content (Bridgeman, Lewis, Heit, & Nagle, 1979). Even within the realm of object recognition, our visual representations are sensitive to the geometric relationships between the object, our bodies, and external frames of reference. For example, our ability to recognize faces depends critically on the in-plane orientation of the face: we are experts at processing upright faces, but this expertise drops dramatically when faces are rotated away from upright, with poorest performance for 180°-rotated (or vertically inverted) faces (Rossion, 2008; Yin, 1969). Although the costs of rotation seem to be higher for faces than for other object categories, many other types of stimuli – furniture, household appliances, written text, and digital displays – also typically appear in regular upright orientations, not only with respect to observers' internal (egocentric) reference frame, but also with respect to external (environmental) reference frames, such as gravity and the surrounding visual environment. How our visual system represents orientation-sensitive information within complex multi-modal environments remains an area of active research.

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Researchers have examined our sensitivity to visual orientation cues at many different levels of processing, from low-level studies of visual discrimination of regular vs. oblique orientations (Appelle, 1972), to mid-level vision studies of mental rotation (Shepard & Metzler, 1971), to high-level studies of object naming and body and face recognition (Chang, Harris, & Troje, 2010; Davidenko & Flusberg, 2012; Lawson & Jolicoeur, 1998; Lloyd-Jones & Luckhurst, 2002; Troje, 2003). In the majority of high-level perception tasks, orientation effects have been attributed more to the perceptual upright than to the subjective visual vertical (Creem, Wraga, & Proffitt, 2001; Dyde, Jenkin, & Harris, 2006; Troje, 2003). For example, when judging whether a rotated character is a ‘p’ or a ‘d’, observers the switching point typically happens when the ambiguous rotated characters are presented at an intermediate orientation between *perceptual upright* (which tracks closely with the observer’s head) and *subjective visual vertical* (which tracks closely with gravity), with greater weight given to the perceptual upright (see Dyde et al., 2006). However, other researchers have shown that depending on the task, the environmental reference frames can sometimes play a dominant role in perception and cognition. For example, how we judge the verticality of a line is systematically influenced by the presence of a tilted surrounding visual frame (*rod-and-frame* effects) and by the tilt of the observer relative to gravity (Asch & Witkin, 1948; Beh, Wenderoth, & Purcell, 1971; Mertz & Lepecq, 2001). Early work by Rock (1956) showed that how an observer interprets an ambiguous shape can depend more on the shape's orientation with respect to gravity than on its orientation with respect to the observer.

Tarr & Pinker (1989) suggested that when we encounter rotated objects, we can adopt one of two strategies to recognize the object. One strategy is to identify an appropriate object-centered reference frame (i.e. identifying the “top” of the object), re-describe the object relative to this reference frame, and solve the recognition problem based on this referenced description (Marr & Nishihara, 1978). An alternative strategy is to mentally rotate the object to a canonical, viewer-centered orientation, and solve the recognition problem based on the canonically represented object (Rock, 1974; Tarr & Pinker, 1989). Evidence for the use of these strategies comes from mental rotation tasks in which observers have to determine, for instance, if two shapes are identical or mirror-reversed. The time it takes observers to make these judgments is an approximately linear function of the angular deviation between the two objects, suggesting that the mental rotation process is gradual and continuous over time (Shepard & Cooper, 1986; Shepard & Metzler, 1971). However, the process of mental rotation can also be influenced by nonvisual factors, such as the cognitive effort required to imagine the object rotating or to imagine ourselves rotating about the object (Macramalla & Bridgeman, 2009).

Recently, researchers have demonstrated that the extent to which orientation effects depend on different reference frames depends critically on the task. For example, Mikellidou, Cicchini, Thompson, and Burr (2015) showed that when participants are standing upright with their heads tilted at 30°, oblique effects in visual discrimination were defined more so relative to the body-centered rather than the head-centered reference frame. However, when participants were lying in a supine position, oblique effects were diminished overall and defined only relative to the head-centered frame. These findings suggest that orientation effects in visual processing are flexibly dependent on gravity; we weigh gravitational cues depending on their salience with respect to our own body’s orientation, but disregard gravitational cues when they are orthogonal to the task or non-existent, such as in microgravity environments (Friederici & Levelt, 1987). Essock (1980) proposed that there are two classes of oblique effects based on the nature of the task. Low-level oblique effects that rely on judgments of orientation or measures of acuity tend to be based on head-centered reference frames, whereas high-level oblique effects that rely on categorization and memory processes tend to depend more on external or environmental reference frames. Overall, research indicates that the reference frame(s) we use to solve a perceptual task will depend on many factors including the nature of the task, the observer’s orientation with respect to gravity, the visual cues to the environment’s orientation, and even the particular method of reporting percepts (Dickerson & Humphreys, 1999; Friederici & Levelt, 1987; McMullen & Jolicoeur, 1990).

Here we investigated how these factors play a role in a real-life task that we often perform during non-upright body positions: reading an analog clock. Consider the following hypothetical situation: you wake up in the morning lying sideways; you glance over at the alarm clock on your night stand, and within a few hundred milliseconds you realize you will be late for work! (see Fig. 1). In this real-life task, the goal is to tell the time quickly, accurately, and with as little effort as possible. As such, this clock reading task may be immune from experimental demand characteristics that typically arise in standard laboratory tasks. In fact, many researchers have examined performance and speed at reading analog clocks to track developmental milestones (Burny, Valcke, and Desoete, 2012), examine multiple routes of cognitive processing (Korvorst, Roelofs, & Levelt, 2007), and investigate multi-word production (Bock, Irwin, Davidson & Levelt, 2003; Meeuwissen, Roelofs & Levelt, 2004). However, to our knowledge, no study has examined the

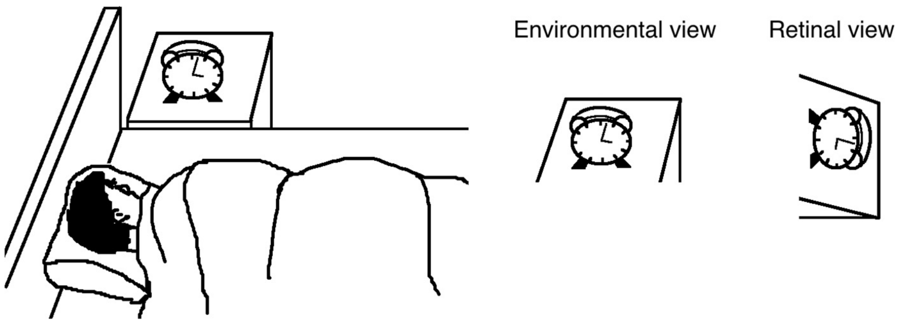

Fig. 1. A schematic of a person lying on their left side while observing an environmentally upright alarm clock. The environmental view of the clock is upright, but the retinal view is rotated clockwise by approximately 90° (minus a few degrees due to ocular counterroll).

effects of stimulus, environment, and observer orientation in clock reading.

We reasoned that analog clocks (such as alarm clocks on a night stand) have a highly stable environmental orientation, and are thus likely to elicit orientation-specific processing with respect to multiple reference frames. Specifically, we have experience looking at and interacting with analog clocks from different body positions (e.g. sitting upright glancing at a wall clock, or lying sideways in bed looking at an alarm clock and planning to hit the snooze button, as in the hypothetical example described above). This suggests that orientation-dependent effects in clock reading are likely to be sensitive to both internal (egocentric) and external (environmental) reference frames.

To assess how these different reference frames interact, we designed a simple clock-reading task in which participants reported the displayed time by pressing 3 buttons (Experiment 1) or a single button (Experiments 2 and 3) on a hand-held number pad. In Experiment 1, we established that when participants are sitting upright, response times depend systematically on the clock's orientation, suggesting the use of a mental rotation-like strategy in solving this perceptual task. In Experiment 2, we dissociated egocentric and environmental reference frames by having participants sit upright or lie sideways, and found that both egocentric and environmental reference frames contribute to response times in the task, though the contribution of the egocentric frame is larger. In Experiment 3, we explored the source of the environmental reference frame effects by the use of an virtual environment (VE) using the Oculus Rift. We placed participants in upright or rotated VEs, while participants themselves either sat upright or lay sideways. This design allowed us to determine whether the environmental reference frame effects observed in Experiment 2 were driven by visual cues, vestibular cues, or a combination of both.

2. Methods and results

2.1. Experiment 1: Does performance in a clock reading task depend on the orientation of the clock?

To determine whether and how clock reading is sensitive to orientation, we designed a simple clock reading task to measure performance and reaction time as a function of clock angle.

2.1.1. Participants

Twenty undergraduates from the University of California, Santa Cruz (15 females, 5 males) gave written consent and received a course credit for their participation. The experimental procedure was approved by UC Santa Cruz's Institutional Review Board.

2.1.2. Stimuli

We generated gray-scale images of analog clocks, as shown in Fig. 2a. The clocks included tick marks at each minute, numbers at each hour, and an hour and minute hand showing the time in 5-minute increments from 1:00 to 9:55. Clocks were displayed at 8 different orientations (0°, ± 45°, ± 90°, ± 135°, and 180°).

2.1.3. Procedure

Participants completed the experiment while sitting upright with their eyes approximately 26 in. from a 22-in. LCD screen. Clock images subtended approximately 8° × 8° of visual angle and were surrounded by a solid gray background. Across 720 trials (8 clock orientations × 9 possible hour hand locations [1–9o'clock] × 10 possible minute hand locations), participants were asked to indicate the time shown on each clock by sequentially pressing 3 digits on the keyboard number pad as accurately and as quickly as possible (one digit for the hour and two digits for the minutes). We recorded accuracy and reaction time as the time elapsed between stimulus onset and the moment the third digit was entered. The experiment lasted approximately 40 min.

2.1.4. Results

We examined the effect of clock orientation on accuracy and reaction time in the clock reading task. A repeated measures 1-way ANOVA showed no significant main effect of clock orientation on accuracy ($F(7,152) = .209$, $p = .983$). In fact, performance was nearly at ceiling, with an average accuracy of 94.1% correct across orientations (Fig. 2b). However, a repeated measures 1-way ANOVA *did* show a significant main effect of clock orientation on mean reaction times during correct trials ($F(7,152) = 2.22$, $p = .036$), with longer reaction times to respond to clocks that deviated away from upright (Fig. 2c). Therefore, for this and subsequent analyses, we focus on reaction times during correct trials, rather than on accuracy.

Individual *t*-tests comparing mean RT at different clock orientations revealed three effects. First, we observed a large "inversion effect", manifesting as faster responses to upright (2.85 sec, 95% CI: [2.63, 3.08]) compared to inverted (3.26 sec, 95% CI: [3.03, 3.50]) clocks ($t(19) = -6.37$, $p = 4.12 \times 10^{-6}$). The difference in mean RT between upright and inverted clocks (402 ms; 95% CI: [276 ms, 528 ms]) indicates a rather large effect of clock orientation on reaction times, equivalent to approximately 2.2 ms delay per degree of rotation, consistent with past studies of mental rotation (Cooper & Shepard, 1984). Second, we found a graded effect of orientation on RTs, with faster mean RT for 0° compared to +90° and −90° clocks ($t(19) = -3.77$, $p = .001$ and $t(19) = -4.68$, $p = 1.62 \times 10^{-4}$, respectively), and faster RTs for +90° and −90° clocks compared to 180° clocks ($t(19) = -5.2$, $p = 5.09 \times 10^{-5}$ and $t(19) = -5.22$, $p = 4.93 \times 10^{-5}$, respectively). Third, we found that the effect of orientation was somewhat asymmetric across clockwise and counter-clockwise rotations. Whereas there was no statistical differences between reaction times to clocks at +45° and −45°($t(19) = -0.39$, $p = 0.70$) or between +90° and −90° ($t(19) = 0.24$, $p = 0.81$), there was a significant difference between reaction times for clocks +135° and −135° ($t(19) = 2.31$, $p = 0.03$), manifesting as slightly longer reaction times for clockwise-rotated 135° compared to counterclockwise-rotated 135° clocks. This advantage for counterclockwise orientations is consistent with

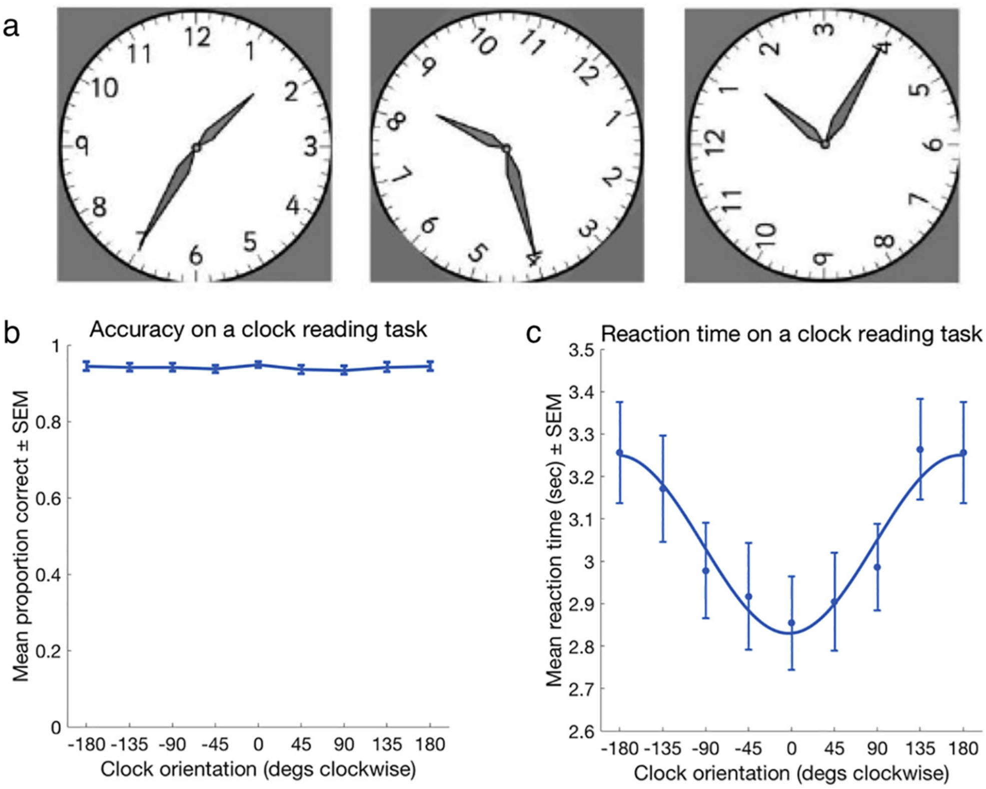

Fig. 2. (a) Example stimuli for the clock reading task used in Experiment 1, shown at 0°, 45°, and −90° (positive angles indicate clockwise rotations); (b) Mean accuracy across 20 participants in reporting the time on clocks, which did not vary as a function of clock orientation; (c) Mean reaction times on correct trials across 20 participants, which did vary systematically as a function of clock orientation. A best-fit sine curve is overlaid on the mean reaction time data. Error bars indicate standard error of the mean.

previous findings of slightly counterclockwise-biased judgments of perceptual upright (e.g. Dyde et al., 2006).

To model the pattern of mean reaction times across clock orientation, we considered two functions: (1) a sine wave with fixed period of 360°, and (2) and a piece-wise linear V-shaped function with fixed width of 360°. For both functions, we fit a single parameter: the phase shift of the curve over the entire span of −180° to 179°. We found that mean RTs were similarly well modeled by the sine wave (with a phase shift of −3°; $R^2 = 0.93$) and the V-shape function (phase shift of −7°; $R^2 = 0.91$). Although the two model fits did not differ significantly from one another, for simplicity, in subsequent experiments we modeled mean RT as a sinusoidal function of the clock angle. To test whether the mean phase shift was significantly different from 0°, we fit individual subjects' RTs and computed the phase shift for each subject. We found that the mean phase shift across subjects (0.3°) did not differ significantly from 0° ($t(19) = 0.05$; $p = .958$), suggesting that the best-fit sine wave to model reaction times is centered at 0°.

2.1.5. Discussion

The results of Experiment 1 confirm that reading analog clocks provides an effective real-life task to study orientation-dependent processing. We found that RTs on correct trials are well modeled by a sinusoidal function of clock angle, with upright clocks leading to the shortest RTs, and inverted clocks leading to the longest RTs. Critically, the effect of clock orientation was large (approximately 400 ms difference between 0° and 180° clocks), which should allow us to tease apart the potential contributions of egocentric and environmental reference frames in the subsequent experiments, where subjects perform the task under different body orientations.

2.2. Experiment 2: What are the contributions of egocentric and environmental reference frames to reaction times on a clock reading task?

To dissociate egocentric and environmental reference frames, a new group of participants completed a simplified version of the clock reading task while sitting upright or lying horizontally.

2.2.1. Participants

Fifty-four undergraduates from the University of California, Santa Cruz (39 females, 15 males) gave written consent and received a course credit for their participation. The experimental procedure was approved by UC Santa Cruz's Institutional Review Board.

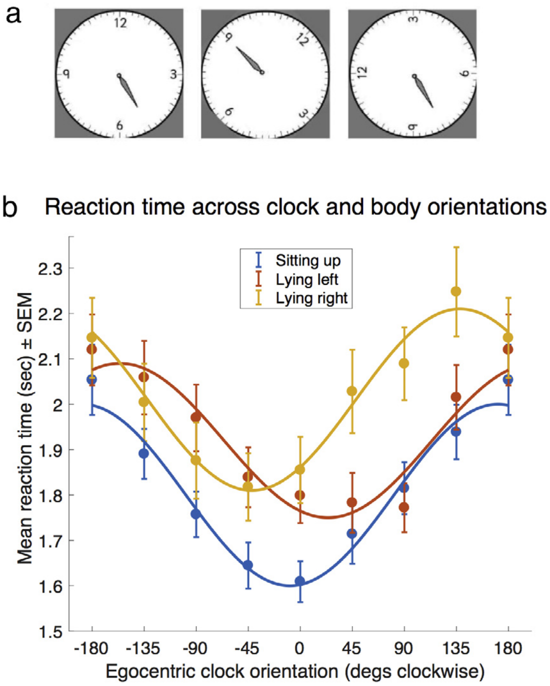

Fig. 3. (a) Example stimuli for the simplified clock reading task used in Experiment 2 with only the hour-hand showing. Participants sat upright or lay sideways (across different blocks) and indicated the time on each clock image by pressing a single button on a hand-held number pad. (b) Mean reaction time on correct trials across 54 participants sitting upright (blue), lying left (red), or lying right (orange), as a function of the egocentric orientation of the clocks. Best-fit sine curves are overlaid on the mean data. Error bars indicate standard error of the mean.

2.2.2. Stimuli

Based on the results of Experiment 1, we modified the clock stimuli and task to obtain more reliable reaction time data and to more easily transport the task to a virtual environment in Experiment 3, where participants would not have visual access to the number pad. Specifically, the clocks included only an hour hand at one of nine positions (hours 1:00 through 9:00; see Fig. 3a) and thus required participants to press only one button to indicate the time. In addition, we included a short training phase (see Procedure, below) to ensure that participants could respond without looking at the number pad (which would be crucial for the virtual reality paradigm in Experiment 3). As in Experiment 1, clocks were displayed at 8 different rotations relative to the observer (0°, ± 45°, ± 90°, ± 135°, and 180°; see Fig. 3a).

2.2.3. Procedure

Before beginning the experimental trials, participants first completed a short training phase, responding to single digit prompts without looking at the number pad. They repeated this until they achieved 8 consecutive correct responses. Once this threshold was reached, participants completed 144 experimental trials (8 clock orientations × 9 clock times [1 through 9o'clock] × 2 repetitions per clock time) in each of 3 body positions (sitting, lying right, and lying left), with the order of body positions counterbalanced across participants. A research assistant stayed in the experiment room to help the participant settle into each assigned body position and to ensure participants did not tilt their heads during the task. Each block of trials began approximately 30 s after the participant had settled into their assigned body position, and each block took approximately 9–10 min to complete, for a total experiment duration of about 30 min.

2.2.4. Results

The pattern of reaction times as a function of clock orientation in the sitting up condition (Fig. 3b-blue) was similar to that in Experiment 1, although reaction times were overall faster due to the simplified clock reading task that required only one button press. A 1-way ANOVA showed a significant main effect of clock angle on RT ($F(7,424) = 6.76$, $p = 1.28 \times 10^{-7}$). As in Experiment 1, there was a large inversion effect, with faster mean RT (1.61sec vs. 2.05 s) for clocks at 0° versus 180° ($t(53) = -8.30$, $p = 3.82 \times 10^{-11}$), equivalent to approximately 2.4 ms cost for every degree of rotation. We also found a graded effect of orientation, with faster mean RT for clocks at 0° compared to +90° and −90° ($t(53) = -5.40$, $p = 1.61 \times 10^{-6}$ and $t(53) = -3.90$, $p = 2.70 \times 10^{-4}$, respectively), as well as faster mean RT for clocks at +90° and −90° compared to 180° ($t(53) = 5.56$, $p = 8.90 \times 10^{-7}$; $t(53) = -6.38$, $p = 4.46 \times 10^{-8}$, respectively). Here, the effect of clock orientation on RT was symmetric across clockwise and counterclockwise orientations, with similar mean RT at +45, +90°, and +135 compared to −45, −90, and −135 ($t(53) = 1.53$, $p = .13$; $t(53) = 1.64$, $p = .11$; $t(53) = 1.12$, $p = .27$, respectively).

A 2-way ANOVA with factors of body orientation and egocentric clock orientation revealed 3 significant effects: (1) a main effect of body orientation ($F(2,106) = 5.93$, $p = .0036$) reflecting slower RTs overall when participants were lying down compared to sitting upright, (2) a main effect of egocentric clock orientation ($F(7,371) = 43.5$, $p = 1 \times 10^{-12}$) reflecting faster reaction times on clocks with smaller egocentric rotations, and an interaction between body orientation and egocentric clock orientation ($F(14,742) = 5.74$, $p = 2.1 \times 10^{-5}$). There was no significant difference in response times between lying right and lying left ($F(1,53) = 2.36$, $p = .13$) but a strong interaction between lying direction and egocentric clock orientation ($F(7,371) = 9.0$, $p = 7.1 \times 10^{-7}$). To characterize the effect of egocentric angle on mean RT across the three body positions, we analyzed data from the different body positions separately, by fitting group-wise and individual sinusoidal curves.

Group best-fits. We modeled the mean RT across subjects as a sinusoidal function of egocentric clock orientation, separately for each body position, fitting the best phase (horizontal shift) to the 8 mean data points. In Fig. 3b, the mean RT across subjects is shown in blue, red, and orange, for the sitting up, lying left, and lying right conditions, respectively. The best-fit sine curve for the mean data was shifted by $-9°$ for the sitting-up condition (blue), by $+24°$ for the lying-left condition (red), and by $-42°$ for the lying-right condition (orange). The shifts for lying left and lying right were both in the direction of environmental upright; that is, when participants were lying sideways, the "optimal" clock orientation estimated to elicit fastest responses was somewhere between egocentric upright and environmental upright.

Individual best-fits. To determine whether the modeled phase shifts differed significantly across body orientations, we fitted each individual participant's data at each body orientation. Participants' mean phase shift in the sitting-up condition was $-9.2°$ (95% CI $[-18°, 0°]$), reflecting a reliable difference from $0°$ ($t(53) = -2.06$, $p = 0.04$). This counterclockwise shift with upright observers is consistent with previous reports of a counterclockwise-rotated perceptual upright (e.g. Dyde et al., 2006). The mean phase shift in the lying left condition was $+23.0°$ (95% CI: $[9.5°, 36.4°]$), significantly greater than $0°$ ($t(53) = 3.42$, $p = 0.0012$) and in the lying right condition it was $-44.2°$ (95% CI: $[-55.7°, -32.7°]$), significantly smaller than $0°$; $t(53) = -7.74$, $p = 2.95 \times 10^{-10}$). Furthermore, the phase shifts differed significantly across body orientations: paired *t*-tests showed significant differences between phase shifts in the sitting-up vs. lying-left conditions ($t(53) = -4.21$, $p = 9.76 \times 10^{-5}$) and between the sitting-up and the lying-right conditions ($t(53) = 4.61$, $p = 2.56 \times 10^{-5}$). The magnitude of the phase shifts also differed between lying left and lying right body positions, with larger absolute phase shift when lying right than when lying left ($t(53) = 2.3$, $p = 0.024$), suggesting an asymmetric effect of body orientation, again consistent with a counterclockwise bias in the perceptual upright.

2.2.5. Discussion

The results of Experiment 2 indicate that clock reading times are not only sensitive to the egocentric orientation of the clock, but also show systematic sensitivity to the clock's environmental orientation when participants' bodies are tilted. To quantify the contribution of the different factors, we ran a multiple regression model considering factors of egocentric angle, environmental angle, and participants' orientation (coded by two dummy variables indicating whether the participant lay left or not, and whether the participant lay right or not) on reaction times to correctly report the time on clocks across the 24 experimental conditions (3 body positions × 8 clock orientations). This regression model revealed significant weights for all of these factors; specifically 0.099 for egocentric clock angle ($p = 4 \times 10^{-7}$), 0.062 for environmental clock angle ($p = 2 \times 10^{-4}$), 0.098 for lying left ($p = 2 \times 10^{-7}$) and 0.056 for lying right ($p = 0.0003$). Together these factors accounted for 92% of the variance in average RTs across participants across the 24 conditions. In particular, these results indicate that egocentric orientation had approximately 60% greater influence on reaction times than environmental orientation. Controlling for egocentric and environmental angle, lying on the left side led to responses about 100 ms slower than sitting upright ($t(136) = 8.24$, $p = .00001$), while lying on the right led to responses about 56 ms slower than sitting upright ($t(136) = 4.69$, $p = .0002$). According to this model, when participants lie sideways, the fastest reaction times are achieved when clocks are oriented approximately 33° away from egocentric upright, toward the environmental upright.

2.3. Experiment 3: Are the environmental reference frame effects in Experiment 2 driven by visual cues, vestibular cues, or both?

Participants in Experiment 2 had many visual and non-visual cues to the environmental reference frame. Since they participated in a brightly lit experiment room, they had visual cues such as the walls, ceilings, and floor, the desk, computer screen, etc., to indicate which way was up. In addition, participants could use vestibular cues (i.e. the force of gravity) and proprioceptive cues (e.g. the feeling of the pillow on the side of the head) to reinforce environment's orientation. In order to dissociate visual from non-visual cues to the environment's orientation, in Experiment 3 participants wore a head-mounted virtual reality display (Oculus Rift DK1) that placed them in an outdoor virtual environment (VE; see Fig. 4). This VE included trees, a pond, and a visual horizon that provided visual cues to the environmental orientation. Participants completed the same simplified clock task from Experiment 2 while placed in one of these VEs. Across conditions, we manipulated (1) the orientation of the VE to be either aligned with gravity (Fig. 4a and d) or rotated by 90° with respect to gravity (Fig. 2b and c) and (2) the orientation of the observer to be either sitting upright (Fig. 4a and b) or lying right at 90° (Fig. 4c and d). Comparing the pattern of reaction times across these 4 conditions allows us to dissociate the influence of visual and non-visual cues to the environmental reference frames in the clock reading task.

If the environmental reference frame effects observed in Experiment 2 were driven primarily by visual cues, we should observe them whenever the VE is orthogonal to the observer's egocentric reference frame, regardless of the observer's orientation with respect to gravity (conditions B and D). If, on the other hand, the environmental reference frame effects are driven primarily by non-visual (vestibular and/or proprioceptive) cues, we should observe the environmental effects whenever the participant is lying horizontally, regardless of the orientation of the VE (conditions C and D). A third possibility is that both visual and non-visual cues are necessary components to elicit environmental reference frame effects; in this case, these effects of the environmental reference frame should only be observed in condition D, where visual and non-visual cues are aligned to reinforce the (true) environmental reference frame

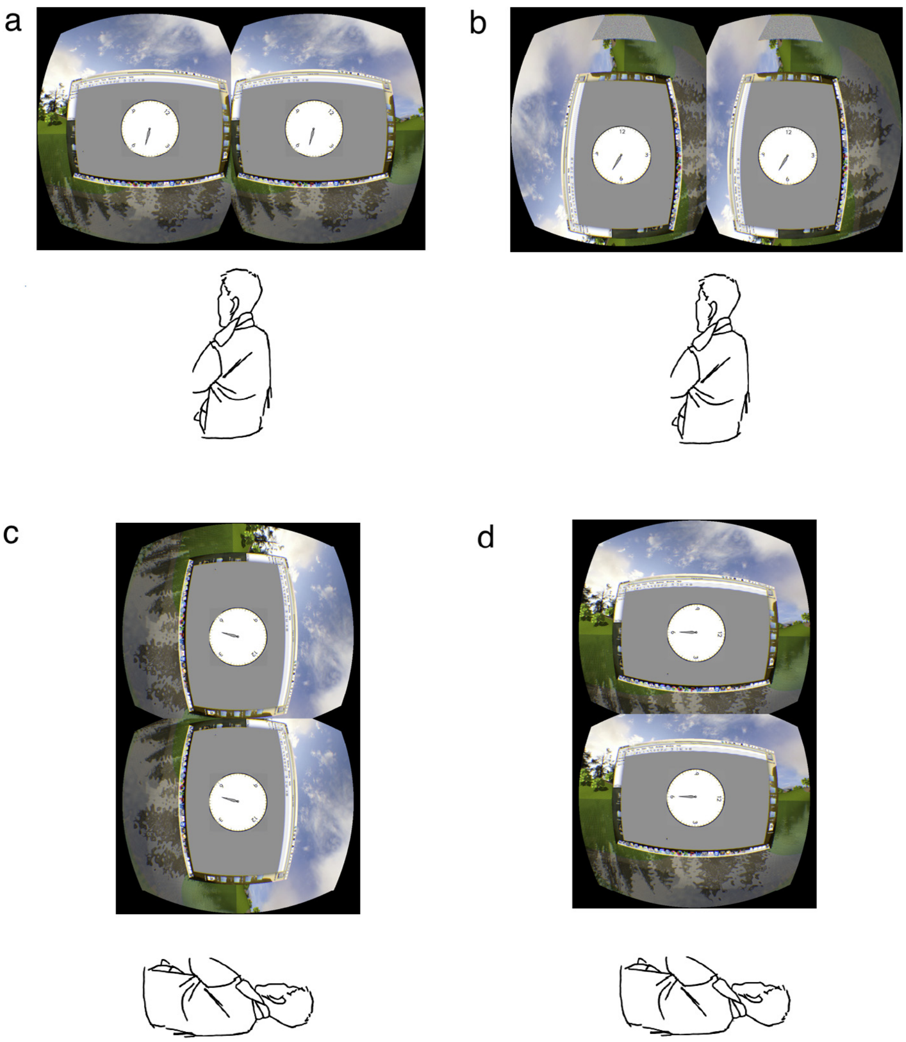

Fig. 4. Example Oculus Rift DK 1 displays for Experiment 3. (a) the observer and VE are upright; (b) the observer is upright, but the VE is rotated 90° to the left; (c) the observer is lying sideways to the right and the VE is egocentrically upright (but environmentally rotated by 90° to the right); (d) the observer is lying sideways to the right and the VE is environmentally upright (but egocentrically rotated by 90° to the left). The two images in each condition represent the information displayed to the left and right eye, producing a 3-dimensional virtual environment.

orthogonal to the observer.

2.3.1. Participants

Ninety-seven undergraduates from the University of California, Santa Cruz (64 females, 33 males) gave written consent and received course credit for their participation. The experimental procedure was approved by UC Santa Cruz's Institutional Review Board.

2.3.2. Stimuli

Participants wore an Oculus Rift DK1 in one of these four conditions: the participant sitting upright with an upright VE (Fig. 4a); the participant sitting upright with a VE that was rotated left by 90° (Fig. 4b); the participant lying on their right side with a VE that was egocentrically upright, but environmentally rotated by 90° to the right (Fig. 4c); or the participant lying on their right side with a VE that was environmentally upright, but egocentrically rotated by 90° to the left (Fig. 4d). The clock stimuli themselves were identical to those used in Experiment 2, but subtended a smaller visual angle, approximately 5.5° × 5.5°, and were shown in lower resolution based on the DK1 display (640 × 800 pixels per eye).

2.3.3. Procedure

Participants were randomly assigned to either two within-subjects conditions (A and B; N = 34), or to one of two between-subjects conditions (C; N = 35, or D; N = 28). Participants in conditions A and B completed the two conditions in a counterbalanced

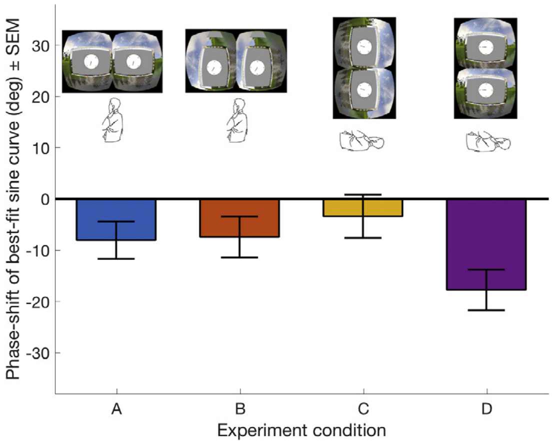

Fig. 5. Results of Experiment 3. Each bar represents the mean phase shift of the best-fit sine curve modeling each participant's response times as a function of egocentric clock angle. A: participants sitting upright with an upright VE; B: participants sitting upright with left-rotated VE; C: participants lying right with egocentrically upright VE; D: participants lying right with egocentrically left-rotated VE. Error bars indicate SEM across participants.

order and used a chin-rest to stabilize their heads while sitting. Participants in conditions C and D lay sideways on a bed and rested their head on a pillow. Participants in all conditions wore a head-mounted display (Oculus Rift DK 1) with an attached level. A research assistant helped the participant settle into the assigned body position (sitting upright or lying sideways) and held on to the Oculus Rift throughout the duration of the experiment, checking the attached level and ensuring participants' heads always remained level at 0° (in conditions A and B) or 90° (in conditions C and D). Each block of trials began approximately 30 s after the participant settled into the assigned body position and took approximately 9 min to complete. The total experiment duration was approximately 20 min for participants in conditions A and B, and approximately 10 min for participants in condition C or D.

2.3.4. Results

We modeled reaction times during correct trials separately for each of the 4 experimental conditions. In each case, we modeled each individual's reaction times as a sinusoidal function of the egocentric orientation of the clocks which appeared at 0°, ± 45°, ± 90°, ± 135°, and 180° relative to the observer. The mean best-fit phase shifts, computed for each observer in each of the 4 experimental conditions, are shown in Fig. 5.

Of the four conditions, the only phase shift that was significantly different than 0° occurred in condition D, where participants lay on their right side with an environmentally upright VE. Here, the mean phase shift was -17.7° (CI: [-25.7, -9.8°]; significantly less than 0; $t(27) = -4.49$; $p = 0.0006$). This suggests that when participants are lying sideways, and the VE is aligned with gravity, the fastest response times are expected when clocks appear 17.7° relative to the observer (in the direction of environmental upright). In the remaining conditions, the mean phase shifts were not significantly different than 0° (all $Ps > 0.15$). The overall pattern of results is consistent with the hypothesis that both visual and vestibular cues to the environment's orientation need to be present, and aligned, to elicit a reliable influence of the environmental reference frame.

2.3.5. Discussion

The results of Experiment 3 begin to elucidate the potential sources of the environmental reference frame effects we observed in Experiment 2. In particular, we found that visual and vestibular cues need to be aligned in order to observe a reliable influence of the environmental reference frame on reaction times; neither visual cues alone nor non-visual cues alone were sufficient to elicit these effects. Even so, the influence of environmental cues in condition D was substantially smaller (mean phase shift of 17.7°) than in the real environment condition in Experiment 2 (mean phase shift of 33.0°). We note that in our VR experiment, the visual cues presented to observers were relatively sparse, and participants were not given a chance to immerse themselves and interact with the virtual environment before completing the clock reading task. Thus, it is possible that a future experiment using visually richer VEs and/or allowing participants more time to immerse themselves in the VEs might enhance these environmental effects in the virtual setting.

3. General discussion

In three experiments, we examined how performance in a real-life clock reading task depends on the orientation of clocks relative to egocentric and environmental reference frames. We found that both egocentric and environmental reference frames influence reaction times, but that the egocentric reference frame has a greater effect. Further, when we dissociated vestibular cues from visual-environmental cues to the environment's orientation by the use of an immersive virtual environment, we found that both visual and vestibular cues were necessary to elicit reliable effects of the environmental reference frame.

Our finding in Experiment 2 of a 33° shift away from egocentric upright suggests that observers may consider more than two "uprights" when engaged in complex visual tasks such as clock reading (see Dyde et al., 2006). That is, this magnitude of the phase-shift does not correspond to either the subjective visual vertical (which would be around 80–85° relative to the observer) or to the perceptual upright (which would be around 10–15° relative to the observer). Instead, optimal performance may use a weighted combination of these two "uprights" to produce a third, intermediate upright direction (closer to perceptual upright than to the subjective visual vertical) to facilitate performance in a given perceptual task.

What are the potential mechanisms by which these various reference frames are combined to influence performance when people read rotated clocks? One possibility is that observers first identify the hour hand, locate the number closest to where the hour hand is pointing (for example, interpolating a hand that points toward the not-shown 8o'clock, as somewhere between 6o'clock and 9o'clock, but closer to 9o'clock), and then mentally rotate these digits in order to make their response. Although this is a potential strategy, it would predict a rather small cost of rotation, given that response times to name rotated single characters are not strongly influenced by the character's orientation (see Corballis, Zbrodoff, Shetzer, & Butler, 1978; Shepard & Cooper, 1986). Instead we posit that participants are more likely to employ a holistic strategy based on an overlearned (upright) clock configuration, that would involve first establishing the clock's orientation with respect to a gravitational reference frame (e.g. finding the "top" of the clock, or the 12o'clock, relative to gravity), and then engage in a mental rotation of the whole clock to read off the time according to this reference frame. McMullen & Jolicoeur (1992) found that the time to find the tops of objects increased continuously as a function of the object's angular deviation from upright, but when subjects tilted their heads by 60°, there was a ~30° shift of the RT curve toward the direction of head tilt, suggesting comparable contributions of head-centered and environmentally-centered reference frames when these two cues are in conflict. Similarly, Friedman & Hall (1996) examined performance in a mental rotation task comparing novel 3D objects (see Shepard & Metzler, 1971) while participants' heads were either upright or tilted. Based on participants' reaction times, they concluded that an upright reference frame is first established relative to either head-centered or environmentally-centered frame, and then the mental rotation is done with respect to that frame. Although the rotated clock reading task we introduced in our current studies did not explicitly require participants to judge the top of the clocks or perform mental rotations, our data suggests participants may have still implicitly established the top relative to the gravitational frame, which would explain the overall increase in reaction times when participants were lying down in either direction, relative to sitting upright. Our results therefore suggest that the initial step of establishing an external reference frame likely occurs across a wide variety of real-life perceptual tasks, and is not limited to tasks that explicitly require identifying object tops or engaging in mental rotation.

3.1. Limitations

The virtual environment in Experiment 3 consisted of a simple landscape with trees, sky, a pond, and a visual horizon. Despite the presence of these visual cues and stereoscopic depth information, some visual cues were still missing. For example, the Oculus Rift provides a constant focal point, so accommodation depth cues were not present. In addition, the relatively low resolution of the Oculus Rift DK1 display may have disrupted the formation of a stable, immersive environment. Finally, we did not give participants time to move around and explore the virtual environment, which is known to increase feelings of immersion (Sanchez-Vives & Slater, 2005). Future studies using richer virtual environments are needed to determine whether visual cues alone (when sufficiently rich) can cause systematic effects of the environmental reference frame on high-level orientation-dependent tasks such as clock reading.

It is also important to note that while participants were asked to indicate the time displayed on the analog clocks, they were not prompted to engage in any physical interaction with the clock. Based on work by Bruce Bridgeman and his colleagues (Bridgeman et al., 1979; Bridgeman, 1996; Macramalla & Bridgeman, 2009) we expect that a planned interaction with the clock might alter the perceptual representations. In particular, if one's intent is to hit the snooze button, one may weigh environmental reference frames more strongly, for example by determining the "top" of the alarm clock with respect to gravity. If one's intent is to simply encode and report the time, then egocentric representations may carry more weight. In fact, depending on the involvement of different sensory modalities in the task itself, different weights may be assigned to different reference frames (see Harris, Carnevale, D'Amour, Fraser, et al., 2015 for a review).

We also note that our study did not measure or control for participants' static ocular counter-roll (OCR), a physiological response that rotates the eyes of tilted observers several degrees toward the environmental upright (see Bischof & Scheerer, 1970; Misslisch, Tweed, & Hess, 2001; Sarès, Granjon, Abdelrhani, and Boulinguez, 2007). In previous work (Davidenko & Flusberg, 2012) we did measure participants' OCR under comparable body tilt and viewing conditions, and found it to be approximately 4.0° (SD: 3.5°), considerably smaller than the effect size of environmental orientation found here under naturalistic viewing (33.0°; see Experiment 2 results) or in a virtual environment (17.7°; see Experiment 3 results). Moreover, further tilting individual participants by their corresponding OCR did not reduce the the contribution of the environmental reference frame to RTs in a face recognition task (Davidenko & Flusberg, 2012). Therefore, we suggest that OCR is not a likely explanation for the effects reported here, although its effects may reduce our certainty regarding the specific weights assigned to the retinal, environmental, and gravitational reference frames in our regression model.

3.2. Implications

Our studies highlight the importance of considering the vestibular and visual environmental reference frames in understanding how we perceive, represent, and recognize regularly oriented objects. By using a real-life clock reading task, we found that response times were highly sensitive to clock orientation, not only with respect to the observer's egocentric reference frame when observers were upright, but also with respect to the perceived orientation of the environment when observers lay sideways. Therefore, we have demonstrated systematic effects of environmental reference frames in a task many of us perform on a daily basis.

Our results have practical implications for the design of remote and head-mounted displays. Even though our results are based on reading analog clocks (which are themselves become less ubiquitous, in favor of digital clocks), we might expect similar contributions of body- and environment-centered reference frames when reading complex displays more generally under different body tilts. For example, mobile displays such as the iPhone are often set up to switch between portrait and landscape modes, depending on the phone's orientation with respect to gravity. However, such algorithms do not consider the orientation of the user's body and head, which may not always be upright with respect to gravity or with respect to the phone's screen. On the other hand, if a mobile display were designed to always align itself with the user's head via head or eye tracking, this solution may also not be optimal either. Indeed, our results suggest that when we are tilted, we seem to prefer an intermediate reference frame that lies somewhere in between egocentrically and environmentally upright (approximately 1/3 of the way from egocentrically aligned to environmentally aligned, when participants lie sideways). Perhaps the best way to design such displays are to allow their orientation to consider both gravity and the observer's head orientation, and use individually defined weights to combine these cues and rotate the display accordingly. As demonstrated by Dyde et al. (2006), these weights may be derived either by measuring visual performance across a range of body and stimulus orientations (and establishing an observer's perceptual upright), or by using Bayesian inference based on the internal error or variability of orientation judgments (see also MacNeilage, Ganesan, and Angelakim, 2008; Alberts, de Brouwer, Selen, and Medendorp, 2016). Practically speaking, the fact that external displays rely primarily on rectangular (as opposed to circular) screens may attenuate the effects of gravitational and external environmental cues, as the screen itself provides strong reference frame (see Corballis, Anuza, and Blake, 1978). However, this rectangular reference frame may not be as salient in wide field of view, head-mounted displays in which the screen edges may be out of view.

The increasing ubiquity of head-mounted displays for gaming, media viewing, and social networking is allowing users to view and interact with visual information in many different body positions and with different access to external reference cues. In particular, as the field of view in head-mounted screens continues to increase, the reference frame produced by the screen itself may lose its influence as its edges go beyond our visual field. With a reduced influence of the display screen, observers using head-mounted displays may rely more on retinal and gravitational cues, especially in tilted body positions such as reclining or lying sideways. Moreover, individuals with limited mobility whose heads are chronically tilted with respect to the body (and gravity) may encounter particular difficulty when viewing screens that are assumed to be viewed from an upright position. Designing optimal displays for such populations will likely require individual assessments of how visual and gravitational cues are combined under different body tilt and viewing conditions. Our results thus have implications for designing head-mounted displays both for the general population and in the context of assistive technologies.

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References

Alberts, B. B., de Brouwer, A. J., Selen, L. P., & Medendorp, W. P. (2016). A Bayesian account of visual–vestibular interactions in the rod-and-frame task. *ENeuro, 3*(5) ENEURO-0093.

Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: The "oblique effect" in man and animals. *Psychological Bulletin, 78*(4), 266.

Asch, S. E., & Witkin, H. A. (1948). Studies in space orientation. II. Perception of the upright with displaced visual fields and with body tilted. *Journal of Experimental Psychology, 38*(4), 455.

Beh, H. C., Wenderoth, P. M., & Purcell, A. T. (1971). The angular function of a rod-and-frame illusion. *Perception & Psychophysics, 9*(4), 353–355.

Bischof, N., & Scheerer, E. (1970). Systemanalyse der optisch-vestibulären Interaktion bei der Wahrnehmung der Vertikalen. *Psychologische Forschung, 34*(2), 99–181.

Bock, K., Irwin, D. E., Davidson, D. J., & Levelt, W. J. (2003). Minding the clock. *Journal of Memory and Language, 48*(4), 653–685.

Bridgeman, B., Lewis, S., Heit, G., & Nagle, M. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5*(4), 692.

Bridgeman, B. (1996). Extraretinal signals in visual orientation. In Handbook of perception and action (Vol. 1, pp. 191–223). Academic Press.

Burny, E., Valcke, M., & Desoete, A. (2012). Clock reading: An underestimated topic in children with mathematics difficulties. *Journal of learning disabilities, 45*(4), 351–360.

Chang, D. H., Harris, L. R., & Troje, N. F. (2010). Frames of reference for biological motion and face perception. *Journal of Vision, 10*(6) 22 22.

Cooper, L. A., & Shepard, R. N. (1984). Turning something over in the mind. *Scientific American, 251*(6), 106–115.

Corballis, M. C., Anuza, T., & Blake, L. (1978). Tachistoscopic perception under head tilt. *Perception & Psychophysics, 24*(3), 274–284.

Corballis, M. C., Zbrodoff, N. J., Shetzer, L. I., & Butler, P. B. (1978). Decisions about identity and orientation of rotated letters and digits. *Memory & Cognition, 6*(2), 98–107.

Creem, S. H., Wraga, M., & Proffitt, D. R. (2001). Imagining physically impossible self rotations: Geometry is more important than gravity. *Cognition, 81*(1), 41–64.

Davidenko, N., & Flusberg, S. (2012). Environmental inversion effects in face perception. *Cognition, 123*, 442–447.

Dickerson, J., & Humphreys, G. W. (1999). On the identification of misoriented objects: Effects of task and level of stimulus description. *European Journal of Cognitive Psychology, 11*(2), 145–166.

Dyde, R. T., Jenkin, M. R., & Harris, L. R. (2006). The subjective visual vertical and the perceptual upright. *Experimental Brain Research, 173*(4), 612–622.

Essock, E. A. (1980). The oblique effect of stimulus identification considered with respect to two classes of oblique effects. *Perception, 9*(1), 37–46.

Friederici, A. D., & Levelt, W. J. (1987). Resolving perceptual conflicts: The cognitive mechanism of spatial orientation. *Aviation, Space and Environmental Medicine, 58*, A164–A169.

Friedman, A., & Hall, D. L. (1996). The importance of being upright: Use of environmental and viewer-centered reference frames in shape discriminations of novel three-dimensional objects. *Memory & Cognition, 24*(3), 285–295.

Harris, L. R., Carnevale, M. J., D'Amour, S., Fraser, L. E., Harrar, V., Hoover, A. E., ... Pritchett, L. M. (2015). How our body influences our perception of the world. *Frontiers in psychology, 6*, 819.

Korvorst, M., Roelofs, A., & Levelt, W. J. (2007). Telling time from analog and digital clocks: A multiple-route account. *Experimental Psychology, 54*(3), 187.

Lawson, R., & Jolicoeur, P. (1998). The effects of plane rotation on the recognition of brief masked pictures of familiar objects. *Memory & Cognition, 26*(4), 791–803.

Lloyd-Jones, T. J., & Luckhurst, L. (2002). Effects of plane rotation, task, and complexity on recognition of familiar and chimeric objects. *Memory & Cognition, 30*(4), 499–510.

MacNeilage, P. R., Ganesan, N., & Angelaki, D. E. (2008). Computational approaches to spatial orientation: From transfer functions to dynamic Bayesian inference. *Journal of neurophysiology, 100*(6), 2981–2996.

Macramalla, S., & Bridgeman, B. (2009). Anticipated effort in imagined self-rotation. *Perception, 38*(1), 79–91.

Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London, Series B: Biological Sciences, 200*(1140), 269–294.

McMullen, P. A., & Jolicoeur, P. (1990). The spatial frame of reference in object naming and discrimination of left-right reflections. *Memory & Cognition, 18*(1), 99–115.

McMullen, P. A., & Jolicoeur, P. (1992). Reference frame and effects of orientation on finding the tops of rotated objects. *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 807.

Meeuwissen, M., Roelofs, A., & Levelt, W. J. (2004). Naming analog clocks conceptually facilitates naming digital clocks. *Brain and Language, 90*(1–3), 434–440.

Mertz, S., & Lepecq, J. C. (2001). Imagined body orientation and perception of the visual vertical. *Psychological Research, 65*(1), 64–70.

Mikellidou, K., Cicchini, G. M., Thompson, P. G., & Burr, D. C. (2015). The oblique effect is both allocentric and egocentric. *Journal of vision, 15*(8) 24 24.

Misslisch, H., Tweed, D., & Hess, B. J. (2001). Stereopsis outweighs gravity in the control of the eyes. Journal of Neuroscience 21(3), RC126-RC126.

Rock, I. (1956). The orientation of forms on the retina and in the environment. *The American Journal of Psychology, 69*(4), 513–528.

Rock, I. (1974). The perception of disoriented figures. *Scientific American, 230*(1), 78–86.

Rossion, B. (2008). Picture-plane inversion leads to qualitative changes of face perception. *Acta Psychologica, 128*(2), 274–289.

Sanchez-Vives, M. V., & Slater, M. (2005). From presence to consciousness through virtual reality. *Nature Reviews Neuroscience, 6*(4), 332–339.

Sarès, F., Granjon, L., Abdelrhani, B., & Boulinguez, P. (2007). Analyzing head roll and eye torsion by means of offline image processing. *Behavior Research Methods, 39*(3), 590–599.

Shepard, R. N., & Cooper, L. A. (1986). Mental images and their transformations. The MIT Press.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703.

Tarr, M. J., & Pinker, S. (1989). Mental rotation and orientation-dependence in shape recognition. *Cognitive psychology, 21*(2), 233–282.

Troje, N. F. (2003). Reference frames for orientation anisotropies in face recognition and biological-motion perception. *Perception, 32*(2), 201–210.

Yin, R. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81*(1), 141–145.