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

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A B S T R A C T

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

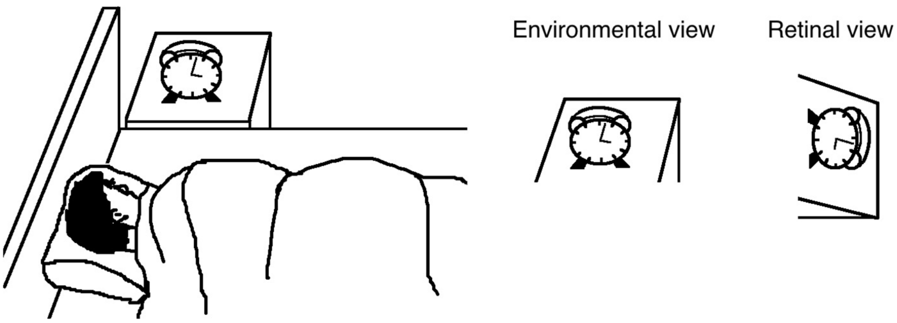

Fig. 1. A schematic of a person lying on their left side while observing an environmentally upright alarm clock. The environmental view of the clock is upright, but the retinal view is rotated clockwise by approximately 90° (minus a few degrees due to ocular counterroll).