Sensorimotor contingency modulates visual awareness of virtual 3D objects

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Abstract

To investigate how embodied sensorimotor interactions shape subjective visual experience, we developed a novel naturalistic Virtual Reality setting combined with motion tracking that allow object interactions with a high degree of freedom, which we implemented within an adapted breaking continuous flash suppression (bCFS) paradigm. This setup allowed us to manipulate the sensorimotor contingencies governing interactions with virtual objects, while characterising the effects on subjective visual experience by measuring breakthrough time to awareness of the virtual objects. We found that breakthrough times were faster for live compared to replayed sensorimotor interactions, demonstrating that visual awareness for unfamiliar 3D virtual objects is influenced by the contingency of the dynamic causal coupling between a person's actions and their visual consequences, in line with theories of perception that emphasise the influence of sensorimotor contingencies on visual experience.

Introduction

The brain engages with the environment through the body, instantiating a closed loop between perception and action. The relevance of these interactions for perceptual phenomenology is emphasized by the Sensorimotor Theory of Consciousness (STC) (Noë, 2004; O'Regan & Noë, 2001). In STC, perceptual phenomenology is shaped by "mastery" of the sensorimotor contingencies governing how sensory signals respond to actions. STC has been applied, conceptually, to many aspects of perceptual phenomenology. One prominent application has been to the phenomenology of "objecthood" in vision. In STC, objecthood depends on the brain's encoding knowledge about how afferent visual signals change given motor actions, such as eye movements. For example, when I experience the coffee cup in front of me as a three-dimensional object with a back-and-sides, it is because my brain "knows about" the sensory consequences of moving my eyes, or rotating the mug. In this sense, I perceive that the mug has a back even though I cannot directly see it (Noë, 2004; O'Regan & Noë, 2001; Seth, 2014). However, empirical tests of the influence of sensorimotor contingencies on perception using realistic or real objects have yet to be achieved, mainly due to the technical challenges of real-time manipulation of sensorimotor contingencies in such contexts.

Here we address this challenge by leveraging recent developments in virtual reality that allow flexible manipulations of the sensorimotor coupling of morphologically complex virtual 3D objects. To investigate how sensorimotor interactions shape subjective visual experience, we combined Virtual Reality technologies with a variant of the binocular rivalry paradigm, known as breaking continuous flash suppression (bCFS) (Stein, Hebart, & Sterzer, 2011; Tsuchiya & Koch, 2005). During bCFS, perception of a target stimulus presented to one eye is suppressed by a series of rapidly changing, high contrast, Mondrian patterns presented to the other eye, and the time it takes the target to 'break through' into awareness is measured.

Experiment

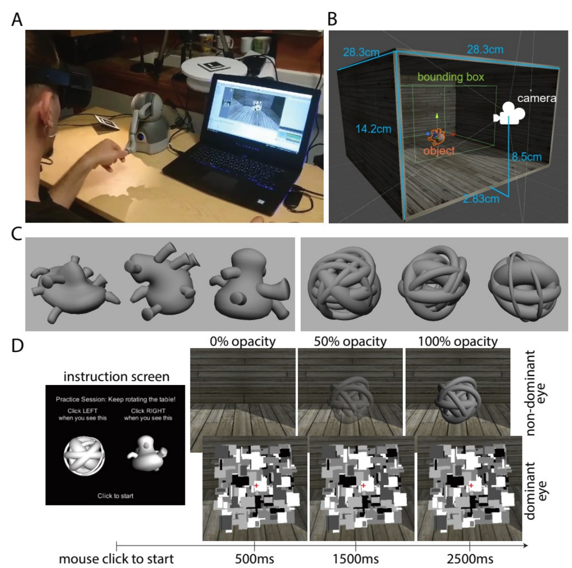

Figure 1: **A**. Experimental setup. **B**. Overview of the virtual environment. **C**. The six virtual objects used in this experiment, divided into two categories. **D**. The objects opacity gradually increased over time and was presented to the non-dominant eye (Top) and the Mondrian mask was presented to the dominant eye (Bottom).

Participants were asked to identify if an object belonged to one of two categories (Figure 1C) presented using the bCFS paradigm, while performing natural unrestricted rotational movements of the object using a stylus attached to a motion-tracking device (Figure 1A). The stylus motion was transferred to the virtual object (Figure 1B). Virtual objects were presented through a head-mounted display to the non-dominant eye, while a dynamic Mondrian mask was presented to the dominant eye (Figure 1D). Participants were required to identify the object, using a mouse-click as quickly as possible.

We compared three aspects of sensorimotor coupling on breakthrough times. In the 'Live' condition, the object responded directly to the participant's rotational movements. In the 'Replay' condition, the object rotated according to the rotational movements of a randomly selected pre-recorded practice trial. To provide a baseline for breakthrough times we added a 'Static' condition, in which the 3D virtual object always maintained the same orientation (apparent visual angle) with respect to the participant. See our published work for more details about the experimental setup and procedure (Suzuki, Schwartzman, Augusto, & Seth, 2019).

Result

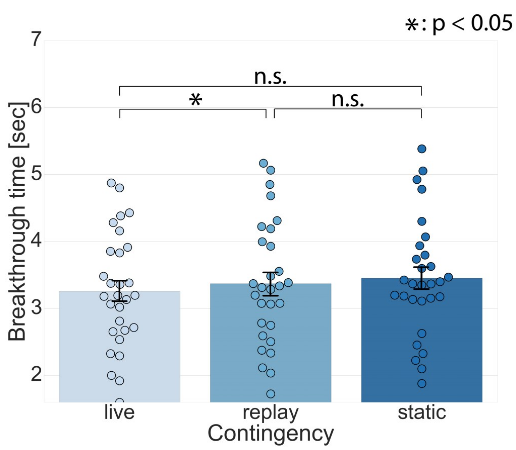

Figure 2: Breakthrough time by sensorimotor coupling type (Live, Replay, Static). Significantly shorter breakthrough times were found for the Live compared to the Replay condition. Dots show individual participant results.

31 participants completed the experiment. 2 participants' data were excluded due to extreme differences in reported and physical rotation speeds. The remaining data were submitted to a 1-way repeated measures ANOVA consisting of the main factors Live/Replay/Static. The results revealed a significant main effect ($F(56,2) = 4.125$, $p=0.021$, $\eta^2 = 0.128$) for breakthrough time, with Live ($M = 3.38$ s, $SE = 0.18$ s) showing shorter breakthrough times compared to Replay ($M = 3.58$ s, $SE = 0.21$ s) or Static coupling ($M = 3.67$ s, $SE = 0.21$ s) (Figure 2). Post-hoc *t*-tests, with Holm–Bonferroni correction, revealed a significant difference in breakthrough time only between Live and Replay conditions ($t(28) = -2.905$, $p_{holm}= 0.021$) (Live/Static: $t(28) = -2.354$, $p_{holm}= 0.052$; Replay/Static: $t(28) = 0.732$, $p_{holm}= 0.470$). These analyses indicate that breakthrough into awareness of virtual objects identity was faster for interactions that were directly coupled to (i.e., contingent upon) participants' movements, compared to Replay or Static trials.

Discussion

We developed a novel combination of Virtual Reality and motion tracking technologies within an adapted breaking continuous flash suppression (bCFS) to explore how manipulations of sensorimotor contingencies affect visual awareness of realistic 3D virtual objects. Our result shows that the sensorimotor contingency of a person's actions and their visual consequences influences access to visual awareness, in line with theories of conscious perception that emphasise embodied sensorimotor interactions.

The effects of sensorimotor contingency on perception has also been investigated using autonomous robotics (Braitenberg, 1986; Buhrmann, Di Paolo, & Barandiaran, 2013). However, empirical studies that attempt to study sensorimotor contingencies in humans and artificial systems remains sparse. Our study provides a novel setup that could be employed to investigate sensorimotor interactions in both human and artificial systems, with the results of both open to interpretation using the theoretical framework of Sensorimotor Theory.

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