



Representing dynamic stimulus information during occlusion



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ABSTRACT

Human observers maintain a representation of the visual features of objects when they become occluded. This representation facilitates the interpretation of occluded events and allows us to quickly identify objects upon reappearing. Here we investigated whether visual features that change over time are also represented during occlusion. To answer this question we used an illusion from the time perception domain in which the perceived duration of an event increases as its temporal frequency content increases. In the first experiment we demonstrate temporal frequency induced modulation of duration both when the object remains visible as well as when it becomes temporarily occluded. Additionally, we demonstrate that time dilation for temporarily occluded objects cannot be explained by modulations of duration as a result of pre- and post-occlusion presentation of the object. In a second experiment, we corroborate this finding by demonstrating that modulation of the perceived duration of occluded events depends on the expected temporal frequency content of the object during occlusion. Together these results demonstrate that the dynamic properties of an object are represented during occlusion. We conclude that the representations of occluded objects contain a wide range of features derived from the period when the object was still visible, including information about both the static and dynamic properties of the object.

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1. Introduction

During daily life, objects constantly move in and out of sight, temporarily depriving us of direct visual information about these objects. However, even though retinal input is disrupted we tend to experience these objects as persisting in space and time (Michotte, 1950). Several studies have shown that both animals and human observers behave as if the occluded object is still present (e.g. Baillargeon, 1986; Churchland, Chou, & Lisberger, 2003; Von Hofsten, Kochukhova, & Rosander, 2007; Van Wermeskerken et al., 2011). This suggests that we maintain an internal representation of an object while it is occluded. This representation of occluded objects has been a topic of interest in several fields investigating situations of both partial and full occlusion. Behavioral studies investigating amodal completion – the process of filling in occluded parts of an object – have shown that both the shape (Rensink & Enns, 1998) and color (Albertazzi, Canal, & Micciolo, 2012; Pinna, 2008) are completed for the occluded segment of the object. This representation of the occluded segment is formed automatically (Murray, Imber, Javitt, & Foxe, 2006) and can

influence both the interpretation of concurrent events (Joseph & Nakayama, 1999; Sekuler & Palmer, 1992) as well as subsequent behavior (Gerbino & Salmasso, 1987). Similarly, studies on full occlusion show that information about object shape, color, velocity, and motion direction can be maintained across periods of occlusion (Flombaum, Scholl, & Santos, 2009; Hollingworth & Franconeri, 2009; Moore, Stephens, & Hein, 2010; Saiki, 2003). This information can be used to track and identify objects across episodes of occlusion (Hollingworth & Franconeri, 2009; Von Hofsten et al., 2007; Scholl & Pylyshyn, 1999), as well as predict events occurring during occlusion (Baillargeon, 1986; Benguigui, Ripoll, & Broderick, 2003; Von Hofsten et al., 2007). Furthermore, it has been shown that an object under occlusion can be the target of object-based attention, suggesting that the representation contains information about feature binding that occurred before occlusion (Behrmann, Zemel, & Mozer, 1998; Moore, Yantis, & Vaughan, 1998). On a neural level, the representation of occluded objects resembles that of visible, non-occluded objects. Several studies have reported a wide network of activity in visual areas of the brain that overlaps with activity found when objects are not occluded. This network includes both visual areas involved in the processing of higher order stimulus information such as object shape (Kourtzi & Kanwisher 2001; Kovács, Vogels, & Orban,

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1995), object identity (Hulme & Zeki, 2007), and relative location (Graziano, Hu, & Gross, 1997), as well as retinotopically mapped areas involved in the processing of basic features of the visual scene (Ban et al., 2013; Rauschenberger, Liu, Slotnick, & Yantis, 2006).

Together, these studies suggest that the representation of occluded objects incorporates a wide range of features, derived from the period that the object was still visible. These features are represented by visual areas of the brain that also represent these features during perception of the visible object (Ban et al., 2013). Furthermore, these representations seem to be object-like in nature (Behrmann et al., 1998) enabling us to understand events that occur during occlusion as well as to categorize objects on reappearance (Baillargeon, 1986; Scholl & Pylyshyn, 1999).

Most studies on occlusion have focused on the static visual properties of an object (e.g. color or shape). However, in many natural situations image properties such as shape, luminance, and location change over time. For example, when a tennis ball temporarily disappears behind a wall, its location continues to change during occlusion. Additionally, if the ball is spinning, its visual features also change along its trajectory. Representing these feature changes and the rate at which they occur could aid in the interpretation of events occurring during occlusion as well as facilitate the identification of objects upon reappearing. For example, a change in velocity or spin would suggest that the object interacted with another object while under occlusion. Up until now, only the change of location over time (motion) has been studied (Olson, Gatenby, Leung, Skudlarski, & Gore, 2004; Von Hofsten et al., 2007; Ban et al., 2013). These studies have shown that both location and speed are represented during occlusion. For example, Olson et al. (2004) reported that activity in human MT/V5 for occluded motion was similar to that observed during visible motion, suggesting that area MT/V5 continues to represent the velocity and direction of the object during its occlusion. In addition, a study by Ban et al. (2013) showed that the retinotopic representation of the position of an occluded object in areas V1 and V2 is updated over the course of the occlusion period. This suggests that the temporal derivative of position – velocity – is used to extrapolate the predicted position of the object during occlusion. It is unknown however, whether dynamic changes other than motion, such as those occurring for the spinning ball, also continue to be represented during occlusion.

Here we present two experiments in which we investigate whether dynamic changes in the visual features of an object are represented during occlusion. To this end, we investigated whether the temporal frequency content of a luminance-modulated (i.e. flickering) object is represented during occlusion. We used a well-known temporal illusion – temporal frequency induced time dilation – in which the perceived duration of an event increases as a result of an increase in its temporal frequency content (Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Ortega & López, 2008). By combining this property of duration perception with a situation in which the object becomes occluded, we can investigate whether the dynamic properties of an object are represented during occlusion. We hypothesized that if the temporal frequency content of an occluded object is represented during occlusion, it should lead to patterns of time dilation similar to those observed during normal, visible presentation.

2. Experiment 1

We presented participants with a duration reproduction task in which participants replicated the duration of a stimulus that was either static or luminance-modulated at different temporal

frequencies. On each trial the stimulus was paired with the presentation of an occluder that moved either in front or behind the stimulus, and then returned to its starting position after a short delay. As a result the stimulus either remained visible or became temporarily occluded. If the temporal frequency content of the stimulus is represented during occlusion we should observe longer reproduction for higher temporal frequency modulations, both for the non-occluded and occluded stimuli.

To assure that participants are aware of the onset, offset, and temporal frequency content of the stimulus, a brief pre- and post- occlusion presentation of the stimulus is needed. These presentations could lead to time dilation, making it difficult to interpret any time dilation found for occluded stimuli. To solve this issue, we added a control condition, in which the stimulus remained visible but the luminance-modulation was faded out and back in over the period in which the occlusion event occurred. This extinction condition simulates the pre- and post- occlusion presentation of temporal frequency content in the occluded condition, without presentation of the deletion (and accretion) cues that would lead to maintenance of the temporal frequency content of the stimulus. As such any effect of initial presentation should occur for non-occluded, occluded and extinction stimuli. On the other hand, any effect of the representation of temporal frequency during occlusion should only be observed for occluded stimuli and not for stimuli with fading luminance-modulation.

To summarize, if temporal frequency is represented during occlusion we should observe time dilation both when the stimulus remains visible as well as when it becomes occluded. Additionally, time dilation for the occluded stimuli should be larger than any time dilation observed in the extinction condition.

2.1. Material and methods

2.1.1. Participants

A total of 20 healthy adults participated in this study (7 male; mean age = 22.5, SD = 3.41). All participants had normal or corrected-to-normal vision and normal stereoscopic vision. They received monetary reward or course credits as compensation for their participation and were naïve as to the purpose of the experiment. The experiment was conducted in line with the principles expressed in the Declaration of Helsinki and received approval by the local ethics committee. All participants were informed that they could stop their participation at any time and that the data would be processed anonymously. After agreeing with these terms all participants signed a written informed consent form.

2.1.2. Apparatus and stimuli

Stimuli were presented on two linearized 24-inch LCD monitors (screen resolution at 1920 × 1080 pixels, 60 Hz refresh rate) controlled by single Windows workstation (Windows 10) running MATLAB 2010A (MathWorks, Inc.) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Both screens were viewed dichoptically through a mirror setup. Throughout the experiment images from the right screen were projected to the right eye and images from the left screen to the left eye. The total distance between the participant and each of the screens was ~85 cm. From this distance the full screen subtended 35.38° × 20.08° of visual angle. Head movements were restrained using a chinrest.

All stimuli were presented on both monitors and were presented on a grey background (62.5 cd/m²). To facilitate binocular fusion between the two images all presentation was accompanied by a square, pink-noise frame (96.79% Michelson contrast) that started 11.2° × 11.4° from the center of the screen and subtended 2.8° × 2.8° of visual angle.

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