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Temporal structure coding with and without awareness

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ABSTRACT

In order to interpret a constantly changing environment, visual events far apart in space and time must be integrated into a unified percept. While spatial properties of invisible signals are known to be encoded without awareness, the fate of temporal properties remains largely unknown. Here, we probed temporal integration for two distinct motion stimuli that were either visible or rendered invisible using continuous flash suppression. We found that when invisible, both the direction of apparent motion and the gender of point-light walkers were processed only when defined across short time periods (i.e., respectively 100 ms and 1000 ms). This limitation was not observed under full visibility. These similar findings at two different hierarchical levels of processing suggest that temporal integration windows shrink in the absence of perceptual awareness. We discuss this phenomenon as a key prediction of the global neuronal workspace and the information integration theories of consciousness.

1. Introduction

When one is immersed in a visual environment, the optical flow is constantly changing as objects move and as one moves in relation to these objects, defining temporal structures (Blake & Lee, 2005). Processing these dynamic cues implies the existence of temporal integration windows within which different aspects of the signal changing over time (e.g., successive positions of a point of light) are integrated into a unified percept (e.g., a moving point). The duration of integration windows can be defined as the maximal delay between two events for which a response differs from the summed responses associated with each event. This reflects the fact that visual features conveyed by temporal structures are not defined at any one point in time, but are emergent properties of temporal integration. We followed this logic and measured temporal integration for apparent and biological motion. In apparent motion, light points alternating between non-contiguous spatial locations are not perceived as flickering, but as moving back and forth (Anstis, 1980). For instance, if two vertically aligned dots are presented alternatively on either side of a virtual rectangle, with a delay less than the temporal integration window, one does not perceive two pairs of dots flickering out of phase, but two single dots moving back and forth along the rectangle's horizontal axis. Perceiving such motion implies that the location of the first point remains available until the second appears (i.e., the signal must be integrated over this duration). In addition, the correspondence between dots must be established, so that the same identity is attributed to two dots from pairs seen at different locations and times (Dawson, 1991). In the given example, a strong bias for horizontal correspondence between the dots creates the percept of horizontal motion, although the display could be as well interpreted as two dots moving along the diagonals of the rectangle.

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Involving more complex motion processing, point-light walkers are points of light representing the structural arrangement of the main joints of a walker across time (Johansson, 1973). Despite their simplicity, one can perceive the gender of point-light walkers, both using structural cues (e.g., the shoulder–hip ratio, larger for males) and kinematic cues (e.g., the lateral body sway, more pronounced for females) (Mather & Murdoch, 1994; Troje, 2002). While structural cues are encoded by the spatial relationships between light points, and are therefore available at each individual image frame, kinematic cues only arise when integrating information across frames. Hence, one can study spatial and temporal integration from structurally and kinematically defined point-light walkers, respectively.

Static spatial features that are defined at any point in time (e.g., location, orientation, color) are known to be encoded and integrated into objects even when these are perceptually invisible (see Lin & He, 2009 for a review). Yet, the integration of such invisible static features into dynamic features (e.g., motion speed, direction, synchrony) has not hitherto been addressed.

In order to assess the role of awareness during temporal integration, we used apparent and biological motion that were either fully visible or rendered invisible by continuous flash suppression (CFS). In CFS, a stream of salient patterns flashed to the dominant eye renders the signal presented to the non-dominant eye invisible (Tsuchiya & Koch, 2005; Tsuchiya, Koch, Gilroy, & Blake, 2006). Relying on previous results (Anstis, Giaschi, & Cogan, 1985; Blake, Ahlström, & Alais, 1999; Geisler, 1999; Jordan, Fallah, & Stoner, 2006; Kruse, Stadler, & Wehner, 1986; Rajimehr, Vaziri-Pashkam, Afraz, & Esteky, 2004; Ramachandran, 1975; Troje, Sadr, Geyer, & Nakayama, 2006; Wiesenfelder & Blake, 1991), we assumed that in the presence of temporal integration, being exposed to apparent motion with a particular direction or a point-light walker with kinematic features (hereafter the adaptor) would bias the way subsequent ambiguous motion is perceived (i.e., apparent motion with ambiguous direction, or point-light walkers with ambiguous gender). By varying parametrically the kinematics and visibility of apparent and biological motion adaptors, we could quantitatively estimate the extent of temporal integration with and without awareness.

2. Methods

2.1. Participants

Healthy volunteers with normal or corrected-to-normal visual acuity were recruited from the campus student population (age range: 18–30). Twenty participants were included in the apparent motion experiments (8 in the visible condition, 12 in the invisible condition, 3 females in each group). Fifty-eight participants were included in the biological motion experiments (visible condition: 9 for structural and kinematic point-light walkers (4 females), 8 for structural point-light walkers (4 females), 7 for kinematic point-light walkers (4 females); invisible condition: 7 for structural and kinematic point-light walkers (5 females), 8 for structural point-light walkers (5 females), 9 for kinematic point-light walkers (5 females); 10 for visible and invisible slow kinematic point-light walkers (1 female)). Subjects were naive to the purpose of these experiments, and gave informed written consent. All experiments conformed to Institutional Guidelines and to the Declaration of Helsinki.

2.2. Apparatus

Stimuli were presented using Matlab and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997). Participants' heads were stabilized using a chinrest located 57 cm away from a 19″ CRT screen (resolution 1024×768; 100 Hz refresh rate). A mirror stereoscope was used to present images separately to each eye.

2.3. Continuous flash suppression

A frame composed of textured black and white bars (0.58° width) was presented to each eye to facilitate stable fusion. Each trial started with a key press, once participants made sure that a fixation dot presented to the dominant eye (0.23° diameter) was centered within a circle presented to the non-dominant eye (1.16° diameter). CFS patterns consisted of arrays of 600 randomly generated disks (from 0.08° to 1.16° diameter) of different shades of gray flashed at 10 Hz to the dominant eye.

2.4. Apparent motion

2.4.1. Stimuli

Stimuli consisted of disks of 1.55° diameter, 0.23 Michelson contrast, convoluted with a Gaussian alpha mask (sigma = 0.96°). In the adaptation phase, the illusion of horizontal apparent motion was produced by presenting these disks for 100 ms alternatively on the long edges of an imaginary rectangle, while vertical apparent motion was produced by presenting them on the short edges.

2.4.2. Aspect ratio procedure

Before the adaptation phase, the rectangle's aspect-ratio was adapted for each observer so that on average, durations of vertical and horizontal motion perception were equal (aspect ratio procedure, see Kohler, Haddad, Singer, & Muckli, 2008). For this purpose, two disks were presented at a time, on diagonally opposite corners of an imaginary rectangle, leading to a bistable alternation of horizontal and vertical motion (motion quartet, see Kruse et al., 1986). First, a motion quartet with an aspect ratio of 1 was presented, (8.7° horizontal and vertical distances between the disks), leading to unambiguous perception of vertical motion. Observers had to report the direction of the quartet motion continuously by holding one of two directional keys. After each period of 2 s, the vertical distance was increased or decreased by 0.4° in order to compensate for the dominant direction perceived during this time window. The optimal aspect ratio was chosen as the average of the vertical distances across ten perceptual reversals (i.e., switch from vertical to horizontal direction). On average, the vertical to horizontal average ratio was