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Vision Research 41 (2001) 3505–3511

Vision Research

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Systematic eye movements do not account for the perception of motion during attentive tracking

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Received 14 November 2000; received in revised form 8 June 2001

Abstract

It has been suggested that attention can disambiguate stimuli that have equal motion energy in opposite directions (e.g. a counterphasing grating), such that a clear motion direction is perceived. The direction of this movement is determined by the observer and can be changed at will. Assuming that the responses of front-end motion detectors are equal for the two opponent directions, it has been proposed that the unambiguous motion perceived with attentive tracking arises from an independent mechanism that monitors the shifts of attention directed to the moving feature of interest. However, while perceiving motion under attentive tracking conditions, observers often report a strong impression that they are making eye movements. In this study, we investigated whether systematic eye movements are present during attentive tracking and, as a result, could be responsible for the subjective experience of movement. We had observers track an object in smooth motion, apparent motion and ambiguous motion, either with eye movements or with attention. The results show that there are negligible eye movements during attentive tracking, which are neither systematic nor correlated with the stimulus. Given that neither eye movements nor retinal image motion can account for subjectively perceived motion, as well as the absence of any other plausible explanation, we find it tempting evidence for an earlier suggestion that the percept of movement must arise from a specialized mechanism.

Keywords: Systematic eye movements; Perceived motion; Attentive tracking; Consciousness; Efference copy

1. Introduction

Motion perception is normally explained by the detection of spatio-temporal variations in the luminance structure of the world. An object with supra-threshold luminance contrast moving over the retinas initiates a process that eventually leads to the perception of an object in motion. We are also able to see a moving object when we move our body, head, or eyes. In such a case, the representation of the moving object on the retina can even be stationary, for example as we smoothly pursue a flying bird. Nevertheless, we perceive this stationary image of the object as being in motion. The brain has several mechanisms at its disposal to compute motion under these conditions. Obviously, an important mechanism is based on efference copy signals, where the movement on the retina is compared to a copy of the signal that is sent out to the eye muscles (e.g. Von Holst, 1954; Haarmeier, Thier, Repnow, & Petersen, 1997). One intriguing possibility is that efference copy cues are also employed by a closely related system, one that uses an efference copy of the shifts of attention towards a feature to signal motion of that

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0042-6989/01/$ - see front matter
PII: S0042-6989(01)00205-X

feature. One phenomenon that might originate from those kind of signals is known as attention-based motion perception (e.g. Cavanagh, 1992[1]). This phenomenon, originally described by Max Wertheimer in 1912 (Wertheimer, 1912, 1961), has recently attracted renewed attention (e.g. Cavanagh, 1992; Culham, Verstraten, Ashida & Cavanagh, 2000; Verstraten et al., 2000). Wertheimer displayed a cross, which he alternated in time with an identical cross that was rotated 45°. Since the stimulus has equal motion energy/correlation strength in both the clockwise and counterclockwise direction, it appears to flicker or to move randomly in the clockwise or counterclockwise direction during passive viewing. Wertheimer, however, also noticed that it is easy to see an unambiguous direction if one of the 'sails' of this windmill stimulus is actively tracked with attention: '[if] the lines stand normal to one another, and the distances are objectively equally favored, then it is *set and posture of attention* [...] that proved decisive in determining whether the rotation was seen towards the right or towards the left.' (our italics, translated in Shipley, 1961; p. 1070). The direction of this subjectively perceived movement is therefore under control of the observer and can be changed at will (see Fig. 1).

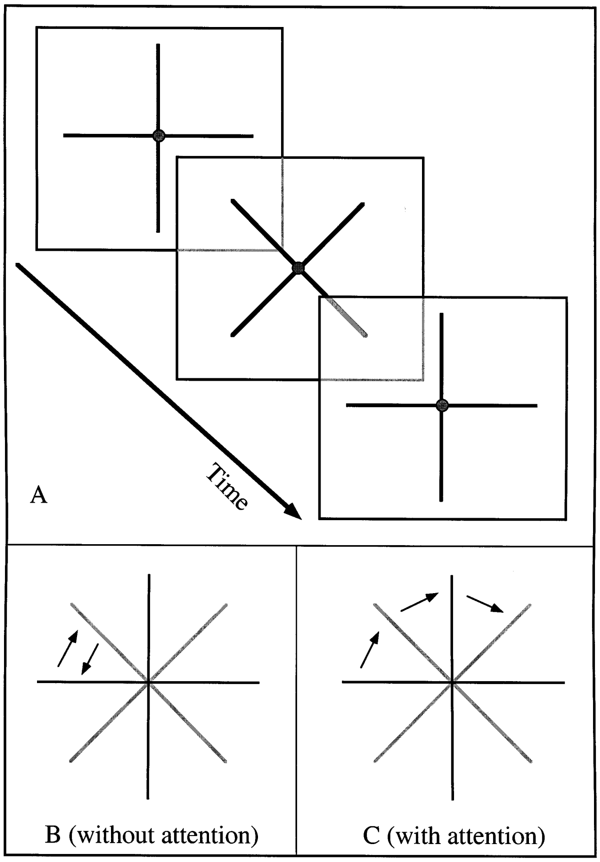

Fig. 1. (A) Stimulus configuration as used by Wertheimer (1912). One cross is alternated in time with a second cross that is rotated 45°. (B) Passive viewing will lead to the impression of back and forth motion or random motion directions. (C) Attentive tracking will result in a configuration that rotates in the direction chosen by the observer. This direction can be changed at will.

This phenomenon is interesting for several reasons. First, the clearly perceived motion direction cannot be explained based on the input of the front-end motion detection system because it supplies the higher processing stages with an ambiguous motion direction signal, if any. Second, assuming that fixation is perfectly maintained, there are no efference copy signals from the eye movement system available to signal motion. Yet, observers experience a clear motion direction when a feature, in this case one of the sails, is attentively tracked. The implication seems that there must be another, attention-based, motion system in our brain.

Before jumping to possibly premature conclusions and introducing new systems, it is important to rule out alternative explanations. Here, we will address one such possibility. According to some, one factor that potentially could account for the effect are eye movements, that is, in demonstrations of the phenomenon, observers who attentively track the stimulus are often skeptical because they have the impression that they are actually making small eye movements. This impression occurs even for observers who are highly trained in fixation and eye-movement tasks. To illustrate this, consider the following situation. One of our observers in the current experiment is highly experienced as an observer in eye-movement experiments. Before we performed the actual experiment, we had this observer become familiar with attentive tracking and tested the accuracy of tracking (see Section 2.1). The task requires only little training, and soon he was performing at a 100% correct level. When we asked what the experienced observer thought of the task, he answered that it was easy but that he was sure that he was making eye movements.

So, the question is 'are there systematic eye movements that could predict the direction and perception of motion during attentive tracking?' So far, the possible role of eye movements under attentive tracking conditions has not systematically been investigated, and it is not clear whether even very small, correlated eye movements are present. We conducted a simple experiment to answer this question, using the most sensitive measure currently available for recording eye movements, a scleral search coil.

[1] This phenomenon is different from the so called *attention-generated motion perception* as described by Lu and Sperling (1995); see also Sperling and Lu (1998) and Verstraten, Cavanagh, and Labianca (2000) for a discussion of some of the differences.

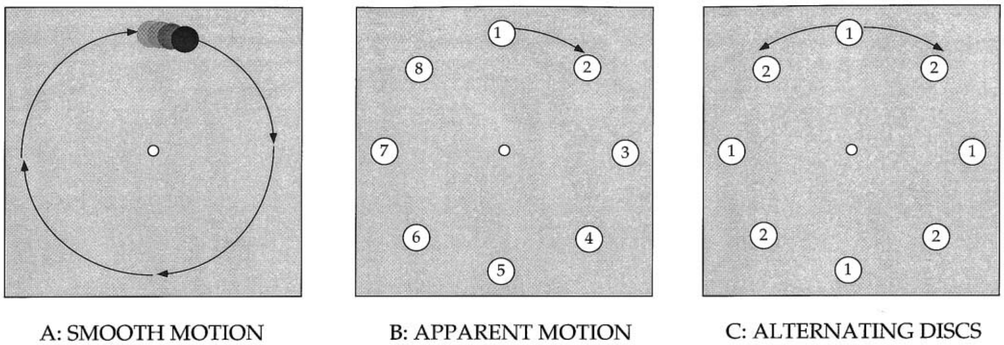

Fig. 2. Stimuli as used in this study: a smoothly moving disc (A: left panel); a disc moving in apparent motion (B: center panel); and two sets of equally spaced discs in alternation that have no net motion energy and are directionally balanced (C: right panel. see text for details). Numbers in the discs indicate the temporal order (1 = first frame, 2 = second frame, etc.).

2. Experiment

2.1. Methods

2.1.1. Stimuli

We used three stimulus configurations, as shown in Fig. 2:

1. A single disc moving smoothly around a circular path.
2. A single disc moving in apparent motion mode along the same circular path (eight disc positions).
3. Two circular arrays of four discs alternating in time and space. The discs were always evenly spaced around the circular array.

All stimuli were presented on a Sony 100 ES 15 inch (38 cm) monitor (vertical refresh rate: 75 Hz, resolution: 1024×768 pixels). Viewing distance: 70 cm; diameter of the circular array: 10.5 cm (e.g. center disc 3 and 7 in Fig. 2B $\sim$ 8.4° of vis angle); the individual discs' diameter: 1 cm (0.8° vis angle); the luminance of the disc: approximately 60 cd m^{-2}, presented on a 10 cd m^{-2} background. The temporal onset and offset of the individual discs in condition B and C followed a step function. The on/off timing of the discs was set such that one revolution would take exactly 1.5 s. The duty cycle of each disk for stimulus configurations 2 and 3 was 40%. Throughout all tasks (see Section 2.1.5), a central (fixation) mark was present (a bull's eye at the center of the display 0.5 cm in diameter, 0.4° vis angle).

2.1.2. Observers

Three male observers (JG, RW, and FV) participated in the experiments. None shows any visual or oculomotor pathology other than refraction anomalies. The observers had normal or corrected to normal vision. FV and RW are authors on this paper, and both wore coils for the first time. JG was naïve as to the goal of the experiment and is experienced with the search coil technique. Except for the practice trials, JG and RW had no experience in attentive tracking.

2.1.3. Apparatus for measuring eye movements

The orientation of the right eye was measured with an induction coil mounted in a scleral annulus (Skalar Medical, The Netherlands) in an a.c. magnetic field (Remmel Labs, USA). This method was first described by Robinson (Robinson, 1963) and refined by Collewijn and colleagues (Collewijn, van der Mark, & Jansen, 1975). The horizontal and vertical eye orientations were measured at a sampling rate of 1000 Hz. The noise level reached at most 0.05°. The data were stored on the computer hard disk for off-line analysis.

2.1.4. Training and testing of tracking performance procedure

In order to make sure that observers could actually attentively track the stimulus accurately (condition C, arrays of four alternating discs), they were tested in a separate session while wearing the eye-coil. Observers fixated a dot in the center of the display. The trial started with a little marker disc presented in the center of one of the flickering discs. This marker disc made successive steps in a defined direction on each alternation. The observers attentively tracked the disc in which the marker appeared. After 2 s, the marker disappeared, and observers tried to attentively track the disc that had been identified by the marker. After some time, the marker reappeared for a short time either in the correct location for accurate tracking or one step before or after the correct location. The observers had to indicate whether the test disc appeared in the disc they were tracking or not (see Verstraten, Cavanagh, & Labianca, 2000). For our conditions, the two inexperienced observers were performing at the 100% correct level after a few practice trials.

2.1.5. Experimental procedure

Observers sat in front of the monitor. The light in the experimental room was dimmed. To prevent head movements, the observers' heads were kept steady using a chin rest and forehead support. For all stimuli (A, B, and C; see Fig. 2), there were three tasks:

1. Choose and track a disc using eye movements, i.e. no fixation.
2. Fixate the central fixation dot and ignore the stimulus (as an extra control, we added the situation where there was only a fixation dot).
3. Choose and attentively track a disc while maintaining fixation on the central marker.

The observers viewed the stimulus and started tracking at their own convenience. As soon as they indicated that they were tracking the stimulus, eye-movement recording was started. We recorded for at least 10 full revolutions (see Section 3). A full revolution took 1.5 s. The average duration of each trial was about 20 s. Only data recorded during the first 15 s (10 revolutions) were analyzed. Trials were repeated once due to the maximum period of 30 min that observers are allowed to wear the scleral coil (including the practice trials). In total, observers were presented with 21 experimental trials (three stimuli∗three conditions∗two measurements plus three trials for the control condition in which only the fixation dot was present).

3. Results

In Fig. 3, we plot part of the raw eye movement data for the three different stimuli and for the three conditions for one observer (JG). The eye movement tracks for the other observers were similar to those of this observer. A first look at the tracks in Fig. 3 indicates that if there are eye movements under attentive tracking conditions, they must be very small.

The crucial question, however, is whether the eye movements, small as they are, are correlated with the movement of the stimulus in such a way that they could none the less explain motion perception during attentive tracking. We therefore analyzed whether the eye movements made under all conditions are related to the

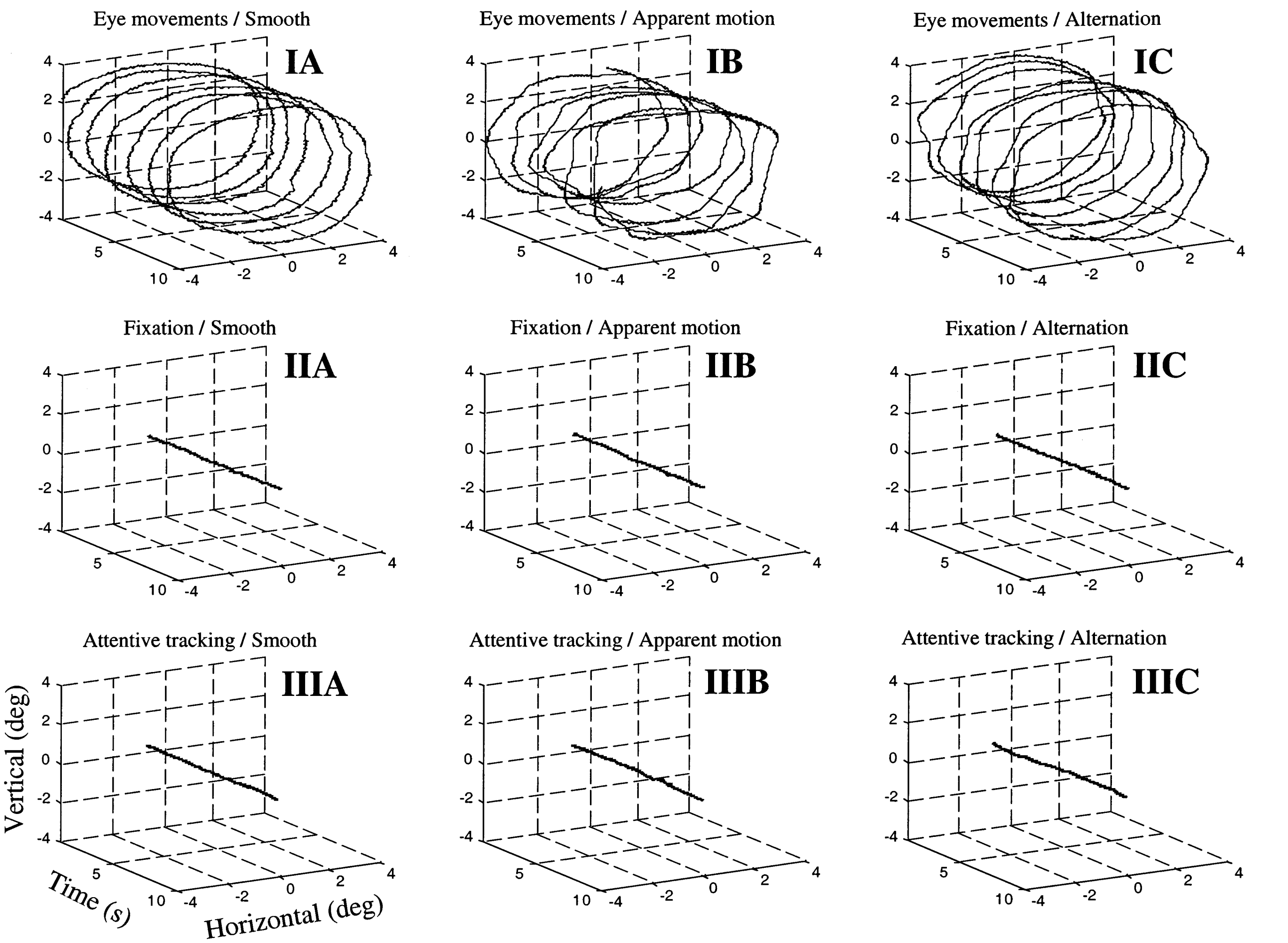

Fig. 3. Results for one observer (JG) for all conditions (Raw sampled data-3 stimuli∗3 conditions − 10 s). The upper row shows the conditions in which the observer tracks (one of) the disc(s) by making eye movements. The middle row represents the passive viewing conditions. In the 'fixation only' condition, the presence or absence of the discs did not result in a significant difference to this condition (results not shown), which shows that observers had no problems fixating in the presence of the stimuli. The panels in the bottom row show the results for the attentive tracking conditions. The results show that the eye movements are negligible and basically the same as for the case in which the observer is passively fixating the configuration (see text for further details).

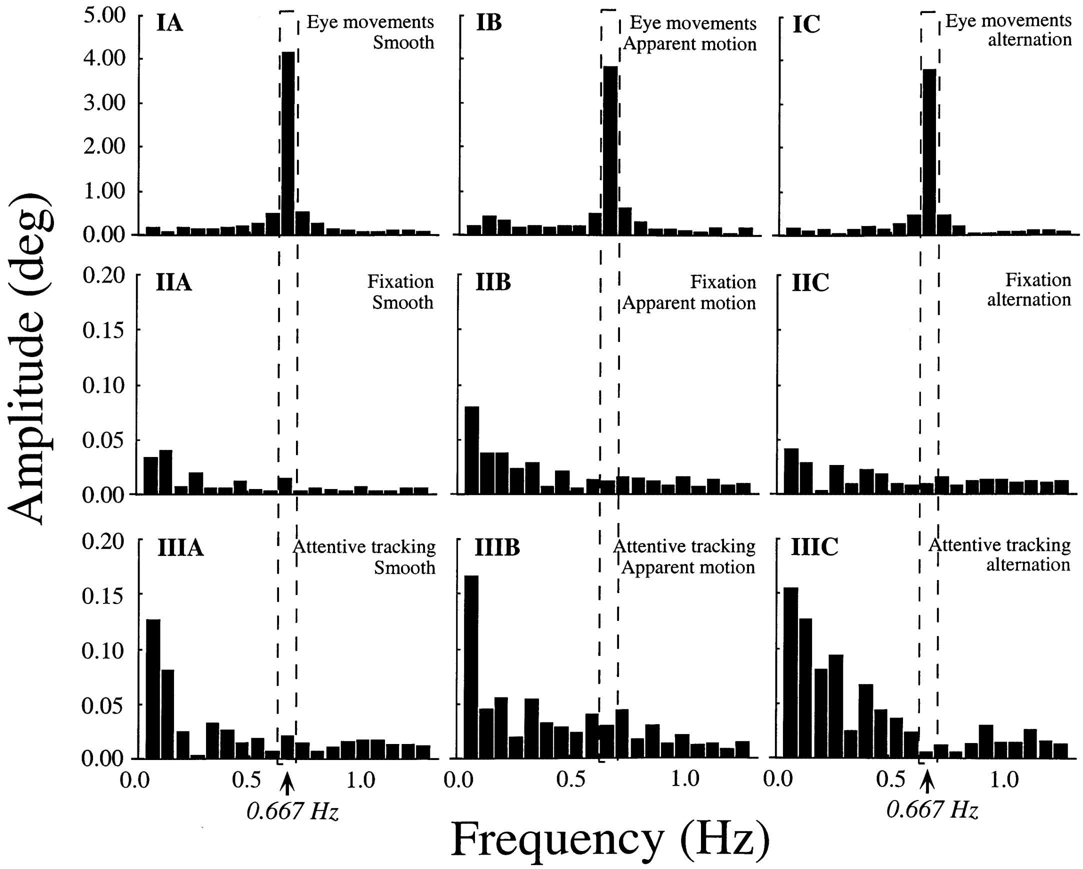

Fig. 4. Frequency content of the horizontal component of the eye orientation for observer FV. These examples are representative for all observers and for the frequency content of the vertical component (note the different scales on the y-axis). The graphs show that for attentive tracking (and fixation), the small eye movements are not correlated with the time course of the stimulus. As it should, for the 'tracking with eye movements' condition, the frequency component of 0.667 Hz is dominantly present.

movement characteristics of the stimulus. To investigate this possible dependency, we determined the frequency content of the eye movement tracks by performing a Fast Fourier Transformation (FFT procedure in MatLab®)

Fig. 4 depicts absolute amplitudes of the horizontal eye movement component for observer FV. We marked the frequency component having a frequency of 0.667 Hz, which is equal to the frequency of stimulus rotation ($1/1.5 = 0.667$ Hz).

As is expected, the data in the figure show that for the eye movement conditions, there is the expected peak in the frequency domain at 0.667 Hz. This 0.667 Hz peak is absent for the fixation as well as the attentive tracking conditions. None of the attentive tracking trials (panel 4IIIA, 4IIIB and 4IIIC) contain a significant frequency component of 0.667 Hz. The most important result is the lack of a 0.667 Hz peak in panel IIIC, which shows that even under attentive tracking conditions, eye movements are not correlated with the perceived subjective motion. There is only a slight increase in lower-frequency components when fixation conditions are compared to tracking conditions (note the scale along the y-axis).

4. Discussion

In a straightforward manner, we have shown that systematic eye movements, even very small movements, cannot account for the percept of movement during attentive tracking. An efference-copy signal explanation can be ruled out, even if one takes the recent discussion about the nature of the contribution/integration of extra-retinal signals in motion perception into account (Wertheim, 1994; Freeman & Banks, 1998; Turano & Massof, 2001). It is more than just likely that even non-linear behavior would have shown up in a systematic way, if there had been a contribution of any eye movements during attentive tracking. However, we *do* perceive motion, and given the absence of a net motion direction in the stimulus and the absence of efferent copy, another system must be responsible for this.

An intriguing possibility is that this alternate system does work on a kind of efference copy, for the shifts of attention required to keep attention locked on the moving feature, rather than the shifts of the eye required to keep the fovea locked on the moving feature. This proposal of 'covert efference copy' was originally suggested by Cavanagh (1991), and it implies that, somewhere in the brain, there must be a system that keeps track of the movement of the focus of attention. A copy of this 'attentive' position change can act as the spatial parameter in a space–time correlation. There is a growing amount of evidence suggesting that this attention-based motion perception system exists. Some of its characteristics are known. For example, we know that it must, at one point, interact with higher-level motion systems because attentive tracking results in a motion aftereffect (Mather, Verstraten, & Anstis, 1998), even in the absence of unambiguous front-end stimulation (Culham et al., 2000; see also Culham et al., 1998 for an overview).

We now know that it is highly unlikely that eye movements play a role in the perception of motion during attentive tracking. Our analysis was only designed to find out whether or not there are systematic eye movements during attentive tracking conditions. However, there are still many interesting questions unanswered. One of these questions concerns the role of eye movements at the time the attention-based movement is started. In a perfect world, that is a directionally perfectly balanced stimulus set-up under passive viewing conditions, there is a balance in motion energy, and hence flicker is perceived. However, it is not clear whether a small or short eye movement is enough to break this delicate balance and tip the scales in favor of one of the possible motion directions. As said, this question is interesting but beyond the scope of this paper (and hard to address experimentally). Here, we are particularly interested in the presence of systematic eye movements *during* attentive tracking. Also, it is unlikely that a small, transitory eye movement, possibly used to kick-start the process, has so much momentum that it is responsible for the percept of motion for such a long time.

Another intriguing question that remains is why some observers insist that their eyes move under attentive tracking conditions, even for highly experienced observers as our subject discussed in Section 1. At this point we can only speculate on the possible answer. One lead is Rizzolatti's *premotor theory of attention* (e.g. Rizzolatti, Riggio, Dascola, & Umilta, 1987). In a nutshell, his theory assumes that a shift of attention is equivalent to an eye movement that is suppressed rather than executed. Under normal circumstances, the eyes move to the object that 'draws our attention'; an observer wants to project the object of (potential) interest on the retina where the spatial resolution is the highest, the fovea. In our experiment, the observer has to maintain fixation, which, from that perspective, is an unnatural condition. The reason that observers report eye movements might have to do with the origin of a signal that is responsible for the 'conscious' experience of eye movements. In order to make a shift of the focus of attention, the brain needs to have an initial set of spatial coordinates. As said, according to Rizzolatti's theory, a shift of attention is normally followed by an eye movement. Even when the eye movement is not executed because the observer has been instructed to maintain fixation, the eye movement signal (but not the corresponding veto) could be processed to the level at which consciousness records that 'the eyes have moved', hence the the subjective experience. From a coding point of view, this is an economical strategy; why would the system recalculate the initial coordinates for the eye movement if it has the parameter values available from the movement of the focus of attention? It is tempting to suggest the existence of such a system, but conclusive evidence is not available at this time.

Acknowledgements

Part of this work was done while F.V. was at the University of Toronto. The hospitality of the members of the UT visionlab is gratefully acknowledged. We are also grateful to the members of the Collewijn lab in Rotterdam, especially Maarten Frens and Jos van der Geest, moreover, to Luiz Gawryszewski, Eileen Kowler and the reviewers for helpful suggestions and discussion. Preparation of this manuscript was supported in part by the Royal Netherlands Academy of Arts and Sciences (KNAW) and a travel grant from the Netherlands Organisation for Scientific Research (NWO) to F.V., a McDonnell-Pew Program in Cognitive Neuroscience grant to J.C., and a NWO *verniewingsimpuls* grant to R.W.

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