Control of binocular gaze in a high-precision manual task

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ABSTRACT

We investigated the precision of binocular gaze control while observers performed a high-precision manual movement, which involved hitting a target hole in a plate with a hand-held needle. Binocular eye movements and the 3D-position of the needle tip were tracked. In general the observers oriented their gaze to the target before they reached it with the needle. The amplitude of microsaccades scaled with the distance of the needle tip. We did not find evidence for the coordination of version and vergence during microsaccades which could be expected if those movements displaced gaze between the needle and the target hole. In a control experiment observers executed small saccades between marks on a slanted plane. Even when the observers executed saccades as small as the microsaccades in the needle experiment, we observed a coordinated displacement of the point of gaze on the horizontal and depth axis. Our results show that the characteristics of eye movements such as the frequency and amplitude of microsaccades are adapted online to the task demands. However, a coordinated control of version and vergence in small saccades is only observed if a movement of gaze on a slanted trajectory is explicitly instructed.

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1. Introduction

Humans are often faced with tasks which require an online coordination of eye and hand movements, such as manipulating static objects or intercepting moving ones (e.g. Land, 2006, 2009). Most often in everyday tasks the eyes are directed to task-relevant locations before the hand, or the tool that extends it, reaches them. For instance, in the process of making a sandwich our eyes will fixate the area where the bread is about to be cut by the knife (Hayhoe et al., 2003). This is a general strategy which observers apply both in pointing tasks (Desmurget et al., 1998) and in more complex tasks, as soon as the observers learn how to perform them (Sailer, Flanagan, & Johansson, 2005).

Generally, the tasks we have to fulfill require us to move our hands or to use our hands to move objects over relative large distances. This implies that if we would keep our eyes on the initial position, the target position would be viewed peripherally. Peripheral vision is characterized by lower acuity (Wertheim, 1894), so it is convenient to perform at least one saccade and foveate the target position. Sometimes, however, we are confronted with tasks which require us to produce extremely small but precise movements of our hands or fingers, typical examples being threading a needle, assembling a clock, removing a splinter or aiming a rifle. Under those conditions most of the relevant objects or object parts would

be viewed foveally, and the question arises as to whether a precise control of gaze position is still required. One class of eye movements which potentially could contribute to orient gaze over small distances is microsaccades. In particular, it has long been debated whether in such tasks microsaccades take the role that saccades have when we visually explore our environment, i.e. orienting gaze towards relevant locations. The first suggestion in this sense came from Steinman et al. (1973) and the first study to address this question was conducted by Winterson and Collewijn (1976). They found that microsaccade frequency was reduced while observers tried to thread a needle or aim a rifle and concluded that microsaccades were not likely of any use in such high-acuity tasks. This conclusion was supported by the results of a subsequent study where observers performed a high-acuity task which did not require any motor response (Bridgeman & Palca, 1980). Furthermore, Kowler and Steinman (1977, 1979) failed to show any improvement in the performance of observers trying to count the elements within a 30 arcmin uniform array when microsaccades were allowed. At this point the general view was that microsaccades were a somewhat puzzling aspect of oculomotor behavior. On the other side, evidence suggesting that microsaccades and saccades might have quite a lot in common was available very early and has been accumulating over the years (for a recent review see Martinez-Conde, Otero-Millan, & Macknik, 2013). Notice however that it has been questioned whether this applies to the extremely small microsaccades (under 10–13 min of arc) that were typically observed in the

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early studies where optical lever devices were used as opposed to the now more common video-based, scleral coil or dual Purkinje eye trackers (Collewijn & Kowler, 2008). The first evidence connecting microsaccades and large-scale saccades emerged as Zuber, Stark, and Cook (1965) showed that microsaccades and saccades have similar kinematic profiles, suggesting a common origin within the oculomotor system. Moreover, Timberlake et al. (1972) showed that small saccades can occur in response to displacements of the fixation point as small as 10 min of arc, and Haddad and Steinman (1973) found that observers were able to voluntarily produce saccades as small as the microsaccades they observed during fixation. More recently, neurophysiological studies connected the execution of microsaccades to the activity of cells in the rostral pole of the superior colliculus (e.g. Hafed, Goffart, & Krauzlis, 2009; Munoz & Wurtz, 1993). It has also been shown that the inactivation of the rostral Superior Colliculus induces a reduction in the frequency of saccades and microsaccades during fixation (Goffart, Hafed, & Krauzlis, 2012). The general picture is that oculomotor space is represented in a continuous retinotopic map in the SC, from caudal neurons coding for large saccades to rostral neurons coding for small saccades (Hafed, 2011). Crucially, a few behavioral studies again suggested that microsaccades might be functionally equivalent to saccades. Microsaccades can occur for instance while observers scan natural images (Mergenthaler & Engbert, 2010; Otero-Milian et al., 2008) and their kinetic properties are not qualitatively different from the ones of microsaccades executed during fixation or large explorative saccades (Otero-Milian et al., 2008). Furthermore, if the size of the images is decreased, so do the amplitude and peak velocity of saccades, smoothly approaching the parameters of fixational microsaccades (Otero-Millan et al., 2013). Most importantly for the purpose of the current study, new evidence has emerged detailing the role of microsaccades in high-acuity visual tasks. Ko, Poletti, and Rucci (2010) measured eye movements while observers performed a needle-threading task in a simulated environment. Although they replicated the finding by Winterson and Collewijn (1976) and Bridgeman and Palca (1980) that the rate of microsaccades decreases towards the end of a trial, they were able to show that in such a task microsaccades contribute to displacing the line of gaze between relevant locations (i.e. the thread and the needle). Towards the end of the trial microsaccades became smaller in size and fewer in number because the two objects were substantially overlapping. This result is perfectly justified if one considers that visual acuity is not homogeneous even within the foveola and drops already 10 arcmin away from the preferred retinal locus of fixation (Poletti, Listorti, & Rucci, 2013).

Most of the studies that have been used in the past to investigate eye movements in high-precision tasks involved either stimuli presented on a screen (Ko, Poletti, & Rucci, 2010; Kowler & Steinman, 1977, 1979; Poletti, Listorti, & Rucci, 2013) or objects which were aligned on the frontoparallel plane (Bridgeman & Palca, 1980) and recording was normally monocular. Nonetheless everyday tasks can require looking at different depth levels and, at least when large saccades have to be performed, there is clear evidence that eye movements can be coordinated binocularly (e.g. Malinov et al., 2000). Binocular oculomotor coordination is potentially important in tasks where the precise position of objects in space has to be estimated from binocular disparity, indeed Ukwade, Bedell, and Harwerth (2003a, 2003b) showed that stereopsis is degraded as soon as vergence error produces a pedestal disparity of around 1.5′. It has long been known that fixational microsaccades are binocular (e.g. Ditchburn, 1955; Møller et al., 2002; Otero-Millan, Macknik, & Martinez-Conde, 2014; Schulz, 1984; St.Cyr & Fender, 1969), but it is not clear whether microsaccades contribute to reduce vergence error during fixation (e.g. Engbert & Kliegl, 2004) or whether vergence errors are corrected

mostly through slow control (e.g. Møller, Laursen, & Sjolie, 2006). Recent evidence supports the idea that fixational saccades can reduce the amount of vergence error induced by pictorial cues to depth (Pérez Zapata, Aznar-Casanova, & Supèr, 2013). Finally, Van Horn and Cullen (2012) demonstrated that at least at the level of the brainstem, premotor neurons code integrated commands for version and vergence during microsaccades, similarly to what has been observed in the case of large-scale saccades.

In summary, there is a consistent body of evidence supporting the idea that oculomotor control in high-precision tasks and in exploration tasks does not differ qualitatively and that in such tasks microsaccades might have a function similar to the one of saccades in exploration tasks. It is not yet known, however, whether this picture extends to binocular control of gaze in an everyday situation where the relevant objects in the workspace are on different depth planes. In the present study we measured binocular eye movements and the position of a needle which the observers tried to insert in a small hole in a plate by executing a precise movement on a slanted trajectory. As a comparison, we also studied the binocular control of eye movements as observers executed small saccades along a slanted plane.

2. Methods

2.1. Observers

Six students from the Justus-Liebig University of Giessen volunteered for the main experiment (all female, mean age 24.2 years). Five of the observers were available to take part in the instructed saccade experiment. All observers were right-handed and reported having normal visual acuity and binocular vision. Participants in the study provided written informed consent in agreement with the Declaration of Helsinki. Methods and procedures were approved by the local ethics committee LEK FB06 at Giessen University (proposal number 2009-0008).

2.2. Eye movements measurement and calibration

Eye movements were recorded binocularly at 500 Hz using an Eyelink II head-mounted infrared video-based system (SR Research, Missisauga, Canada). Head movements were limited, though not excluded by the use of a chin rest. The calibration procedure started with a standard 9-point calibration on a 23-in. Cathode Ray Tube monitor at 46 cm viewing distance. Subsequently, a custom 3D calibration procedure was performed. For the 3D calibration, observers were asked to look sequentially at a series of nine marks located on a mobile metal plate. The procedure was repeated three times with the plate positioned at three depth levels (see Fig. 1a). The distance between two adjacent points and between the depth levels was 30 mm so that the position of binocular gaze was acquired on a $3 \times 3 \times 3$ cubic grid with 60 mm side. The center of the cubic grid was approximately at 20 cm viewing distance.

The calibration procedure was followed by a validation procedure. To this purpose the plate was rotated 45° first clockwise and then counterclockwise. The observer looked in sequence at the three points at mid-height in each orientation (see Fig. 1b).

Both for the calibration and the validation procedures the experimented paced the acquisition by pressing a key when the observer looked at the instructed point. A specific point could be re-acquired if the observer had blinked or eye position signal was lost. For each point eye position was averaged in a 21 sample time window centered on the experimenter's keypress.

The binocular eye movements traces were codified in terms of head-referenced angles using the EyeLink software and the appro-