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The effects of monocular viewing on hand-eye coordination during sequential grasping and placing movements

David A. Gonzalez, Ewa Niechwiej-Szwedo *

Department of Kinesiology, University of Waterloo, Canada

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ABSTRACT

The contribution of binocular vision to the performance of reaching and grasping movements has been examined previously using single reach-to-grasp movements. However, most of our daily activities consist of more complex action sequences, which require precise temporal linking between the gaze behaviour and manual action phases. Many previous studies found a stereotypical hand-eye coordination pattern, such that the eyes move prior to the reach initiation. Moving the eyes to the target object provides information about its features and location, which can facilitate the predictive control of reaching and grasping. This temporal coordination pattern has been established for the performance of sequential movements performed during binocular viewing. Here we manipulated viewing condition and examined the temporal hand-eye coordination pattern during the performance of a sequential reaching, grasping, and placement task. Fifteen participants were tested on a sequencing task while eye and hand movements were recorded binocularly using a video-based eyetracker and a motion capture system. Our results showed that monocular viewing disrupted the temporal coordination between the eyes and the hand during the place-to-reach transition phase. Specifically, the gaze shift was delayed during monocular compared to binocular viewing. The shift in gaze behaviour may be due to increased uncertainty associated with the performance of the placement task because of increased vergence error during monocular viewing, which was evident in all participants. These findings provide insight into the role of binocular vision in predictive control of sequential reaching and grasping movements.

1. Introduction

In most everyday situations information about the environment is acquired from both eyes simultaneously. Integration of the input from both eyes provides unique advantages, which are not available during monocular viewing: binocular summation (Jones & Lee, 1981), binocular disparity (Bingham, Bradley, Bailey, & Vinner, 2001; Fielder & Moseley, 1991; Hibbard & Bradshaw, 2003; Howard & Rogers, 2002; Melmoth, Storoni, Todd, Finlay, & Grant, 2007), and disparity vergence (Bingham et al., 2001; Melmoth et al., 2007; Mon-Williams & Dijkerman, 1999; Tresilian, Mon-Williams, & Kelly, 1999). Numerous kinematic studies have shown that binocular vision provides advantages during the performance of a single prehension movement (Bruggeman, Yonas, & Konczak, 2007; Greenwald & Knill, 2009; Heath, Neely, & Krigolson, 2008; Jackson, Jones, Newport, & Pritchard, 1991; Keefe, Hibbard, & Watt, 2011; Loftus, Servos, Goodale, Mendarozqueta, & Mon-Williams, 2004; Marotta & Goodale, 2001; Servos & Goodale, 1994; Servos, Goodale, & Jakobson, 1992; Watt & Bradshaw, 2000; Westwood, Robertson, & Heath, 2005). For example, one of the advantages may be due to binocular disparity, which provides exteroceptive information about object properties, such as its size, orientation, and shape, which facilitates grasp planning and execution. On the other hand, ocular vergence provides an important depth cue for planning the reach transport component. Consequently, during monocular viewing it is more difficult to accurately localize objects in 3D space which leads to longer reach deceleration interval, larger grip aperture, and longer grasp application time (Melmoth & Grant, 2006).

Recent studies have shown that when binocular vision is not available or is degraded, motor performance in terms of movement time and accuracy, is affected to a greater extent for high precision sequential task, such as bead threading in comparison to the performance of a peg-board task or a water-pouring task (Alramis, Roy, Christian, & Niechwiej-Szwedo, 2015; O'Connor et al., 2009; Piano & O'Connor, 2013). For example, total movement time increased by 19% during monocular viewing for the bead threading task as compared to 12% for the peg-board task. These behavioural

* Corresponding author at: Department of Kinesiology, University of Waterloo, 200 University Avenue West, Waterloo, Ontario M5G 1X8, Canada.
E-mail address: eniechwi@uwaterloo.ca (E. Niechwiej-Szwedo).

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studies clearly show that binocular vision provides important sensory input for the performance of high precision tasks involving movement sequences; however, the main limitation of the previous studies is that performance was measured using a stop watch to record the total movement time, so it is unknown which aspects of movement sequencing are most disrupted during monocular viewing. Therefore, the goal of this study was to investigate the contribution of binocular vision to the execution of movement sequences by measuring the temporal coordination between the eye and hand movements while subjects performed a high precision task involving reaching, grasping, and placement.

Removing binocular depth cues can affect grasping because stereopsis provides input regarding the relative depth of the object, which is required for planning accurate grasp aperture. Placing the bead on the needle also requires accurate localization of the needle in 3D space, which may be dependent on ocular vergence. During binocular viewing the muscular effort that is associated with converging at a particular distance can provide reliable information regarding object's absolute location with respect to the observer (Melmoth et al., 2007; Mon-Williams & Dijkerman, 1999; Tresilian et al., 1999). However, during monocular viewing the ocular vergence signal might not provide reliable input regarding direction and distance because of phoria, that is, a horizontal eye deviation, which is often observed in the covered eye of visually-normal observers. For example, Hrynchak, Herriot, and Irving (2010) measured phoria in 50 young, visually-normal observers using eye tracking while subjects fixated a target presented at eye level at a distance of 40 cm. Results showed that phoria ranged between 6 prism diopters (PD) (3.4 deg) of adduction (esophoria) and 19 PD (10.8 deg) of abduction (exophoria). The extent of phoria is affected by the viewing distance as shown by the experiments conducted by Ono and colleagues (Ono & Weber, 1981): phoria is greater when viewing targets that are near (25 cm) compared to targets placed farther away (50 cm). Finally, the direction of phoria can reverse for distances >2 m, such that subjects become esophoric (Owens & Tyrrell, 1991). Importantly, the direction (i.e., eso or exo) and the amplitude of phoria is associated with localization errors predicted based on the laws of visual direction. For example, in the case of exophoria, the apparent target location shifts towards the non-viewing (covered) eye, and the visual axes from the two eyes intersect farther in depth (Mapp, Ono, & Khokhotva, 2007). In summary, there is substantial between-subject variability in the extent of phoria during monocular viewing; however, most visually normal subjects experience exophoria when fixating on objects within the reaching space.

It is important to characterize the role of binocular vision during sequential movements because they are quite different from single pointing or prehension movements. Sequences are composed of multiple action phases that have to be planned and monitored by the central nervous system (CNS) during movement execution (Land, 2009). Thus, successful performance of action sequences requires temporal coordination between the action phases. An important finding from studies of sequential movements is that optimal control and smooth transition between the action phases is dependent on the ability to predict the sensory consequences associated with the termination of the current action phase (Safstrom, Flanagan, & Johansson, 2013). When interacting with objects, predictive control involves the ability to use exteroceptive information about object properties in order to scale grasp aperture and grip forces (Flanagan, Bowman, & Johansson, 2006). If there is a discrepancy between the predicted and actual feedback, the timing of object contact is disturbed (Safstrom & Edin, 2008) and the CNS has to engage in a correction process to ensure successful performance. Because monocular vision provides less reliable input about object location and its features, it is possible that the ability to use predictive control during the performance of action sequences might be reduced, and this may impact the temporal coordination between action phases. Specifically, the temporal coordination between the reaching, grasping and placement phases may be altered if the system is engaged in correcting an error during one of the phases, and this may lead to a delay in the initiation of a subsequent action phase.

Temporal coordination between action phases during the performance of pointing and manipulation tasks has been studied previously using eye tracking (Abrams, Meyer, & Kornblum, 1990; Bekkering & Sailer, 2002; Bowman, Johannson, & Flanagan, 2009; Johansson, Westling, Backstrom, & Flanagan, 2001; Ma-Wyatt, Stritzke, & Trommershauser, 2010; Mennie, Hayhoe, & Sullivan, 2007; Niechwiej-Szwedo, Goltz, Chandrakumar, Hirji, & Wong, 2011; Niechwiej-Szwedo, Goltz, Chandrakumar, & Wong, 2014; Rand & Stelmach, 2010; Sailer, Eggert, Ditterich, & Straube, 2000; Sailer, Flanagan, & Johansson, 2005; Snyder, Calton, Dickinson, & Lawrence, 2002; Song & McPeek, 2009; van Donkelaar, 1997; Wilmut, Wann, & Brown, 2006). During a single reach-to-grasp movement, gaze arrives and remains fixated at the desired target prior to the hand's arrival. It has been suggested that this time frame, between the eye and hand arriving on target, allows visual information to be used to update the ongoing movement. For example, directing gaze to the location where the fingers are subsequently placed on the object may improve aim and grasp accuracy (Brouwer, Franz, & Gegenfurtner, 2009; Cavina-Pratesi & Hesse, 2013; Johansson et al., 2001; Rand & Stelmach, 2010). A strategic control of gaze shifts was also demonstrated during the performance of a bimanual coordination task when both limbs executed aiming movements to targets with different amplitude and size (Riek, Tresilian, Mon-Williams, Coppard, & Carson, 2003). Moreover, a recent investigation into gaze behaviour during learning of a sequential action pattern revealed that after extensive practice, gaze was shifted predictively to the next target prior to the initiation of a manual response (Safstrom, Johansson, & Flanagan, 2014). These findings suggest that predictive gaze control is an important marker of an effective linking between action phases during sequential movements.

The current study examined temporal hand-eye coordination during the performance of a sequential reaching, grasping, and placement task during binocular and monocular viewing conditions with two levels of difficulty of the placement task. Our goal was to assess the contribution of binocular vision to predictive control by examining the temporal coordination between hand and eye movements during the performance of action sequences. Previous studies have shown that binocular vision provides more reliable input about target location and its features leading to faster and more efficient reaching and grasping movements (reviewed in (Melmoth & Grant, 2006). In comparison, reach deceleration interval and grasp application are longer during monocular viewing indicating that the encoding of target location and its features is less reliable, consequently, these encoding errors must be corrected during movement execution. The novel aspect of this study is the prediction that the increased demand placed on feedback corrections during monocular viewing will alter the temporal hand-eye coordination. Our previous study has shown that prehension movements performed during monocular viewing are associated with a longer fixation on the target during the grasping phase (Gnanaseelan, Gonzalez, & Niechwiej-Szwedo, 2014). Because this was shown in a single reach-to-grasp task, we could not determine whether the extended fixation duration affects the stereotypical eye-hand coordination pattern. On one hand, it is possible that the relative temporal coordination pattern is maintained during monocular viewing, that is, the hand movement is initiated after the eyes fixate the target. On the other hand, the prolonged fixation duration could disrupt the temporal coordination pattern. Therefore, a sequential reach-to-grasp and placement task was used in