Hand-eye coordination for rapid pointing movements

Arm movement direction and distance are specified prior to saccade onset

Abstract Visually guided arm movements such as reaching or pointing are accompanied by saccadic eye movements that typically begin prior to motion of the arm. In the past, some degree of coupling between the oculomotor and limb motor systems has been demonstrated by assessing the relative onset times of eye and arm movement, and by the demonstration of a gap effect for arm movement reaction times. However, measures of limb movement onset time based on kinematics are affected by factors such as the relatively high inertia of the limb and neuromechanical delays. The goal of the present study was thus to assess the relative timing of rapid eye and arm movements made to visual targets by examining electromyographic (EMG) activity of limb muscles in conjunction with eye and arm position measures. The observation of a positive correlation between eye and limb EMG onset latencies, and the presence of a gap effect for limb EMG onset times (a reduction in reaction time when a temporal gap is introduced between the disappearance of a central fixation point and the appearance of a new target) both support the idea that eye and arm movement initiation are linked. However, limb EMG onset in most cases precedes saccade onset, and the magnitude of EMG activity prior to eye movement is correlated with both the direction and amplitude of the upcoming arm movement. This suggests that, for the rapid movements studied here, arm movement direction and distance are specified prior to the onset of saccades.

Keywords Eye-hand coordination · Saccades · Pointing · Gap effect · Reaction time · Movement planning · Human

Introduction

Goal-directed arm movements such as reaching or pointing to a visual target are typically accompanied by saccadic eye movements. Several studies have examined the relative timing of eye and hand movements as a way of assessing the potential coupling of the oculomotor and limb motor systems (see Carey 2000 for review). Usually the eyes begin moving toward a target 40–100 ms in advance of hand movement (Angel et al. 1970; Prablanc et al. 1979; Biguer et al. 1982; Jeannerod 1988). In reaction time tasks, onset latencies for the eye and hand tend to be positively correlated on a trial-by-trial basis, suggesting a common source for eye and arm movement initiation (Herman et al. 1981; Fischer and Rogal 1986; Jeannerod 1988; also see Fisk and Goodale 1985). Similarly, a gap effect (a reduction in reaction time when a temporal gap is introduced between the offset of a central fixation point and the appearance of a new target) has been reported for both saccade onset (Saslow 1967; Fischer and Boch 1983; Munoz et al. 2000) and hand movement latency (Herman et al. 1981; Fischer and Rogal 1986; Jeannerod 1988), suggesting a common mechanism of disinhibition that acts both on the oculomotor and limb motor systems (Bekkering et al. 1996; Boulinguez et al. 2001). However, previous studies of eye and arm movements in reaction time tasks have assessed arm movement latencies based on measures of arm position, which is influenced by neuromuscular delays and the relatively high inertia of the limb as compared to the eye. The precise relative timing of efferent signals to the eyes and to the limb therefore remains unclear.

Electromyographic (EMG) recordings of limb muscle activation are more closely related in time to the descending neural drive to the limb motor system and may provide more precise information about the relative timing of eye and limb movement initiation. It is well known that EMG activity for limb muscles begins as much as 100 ms prior to arm movement (Wadman et al. 1980; Karst and Hasan 1991). Taking this into account in combination with the knowledge that, in reaction time
tasks, saccades can precede movement of the arm by 40–100 ms, one may hypothesize that arm movement may be initiated simultaneously with, or perhaps in some cases prior to saccade onset. The goal of the present study was thus to test this hypothesis by systematically examining the relative timing of eye and arm movement initiation using EMG recordings of limb muscles in combination with recordings of eye and limb position.

We show that, in agreement with previous work on eye-hand coupling based on positional measures of limb movement initiation, a positive correlation is observed between onset latencies for eye movement and limb EMG activity, and a gap effect is observed for limb EMG onset. More interestingly, however, we demonstrate that the onset of limb EMG activity is not coincident with saccade initiation – rather, in most cases limb EMG onset occurs in advance of eye movement. In addition, an examination of the portion of limb EMG activity occurring prior to a saccade reveals that both the direction and the amplitude of an upcoming arm movement are specified before the onset of eye movement. These findings further refine our knowledge about the relative timing of eye and limb movement initiation and provide novel information about the relative timing of the specification of eye and limb movement parameters by the oculomotor and limb motor systems in reaction time tasks.

Materials and methods

Subjects

Eleven subjects (eight men, three women) between the ages of 21 and 32 years participated in the study. Subjects reported no history of neurological or musculoskeletal disorders. All subjects provided written informed consent. The procedures used in this study were approved by the University of Western Ontario Ethics Review Board.

Apparatus

Figure 1A shows the experimental setup. Subjects were seated in the dark in front of a glass tabletop, with their right arm abducted at the shoulder and supported by custom made air-sleds (One of a Kind) in a horizontal plane containing the shoulder. The effect of the air-sleds, which were connected to a 40-psi compressed air source, was to support the arm against gravity and to reduce friction during movement. Medium-density Temper foam (Kees Goebel Medical) was used to provide a cushion between the arm and the air-sleds, and as a result the arm was suspended about 10 cm above the surface of the glass tabletop. A computer-controlled LCD projector was used to provide a virtual target projection, with their right arm abducted at the shoulder and supported by custom made air-sleds (One of a Kind) in a horizontal plane containing the shoulder. The effect of the air-sleds, which were connected to a 40-psi compressed air source, was to support the arm against gravity and to reduce friction during movement. Medium-density Temper foam (Kees Goebel Medical) was used to provide a cushion between the arm and the air-sleds, and as a result the arm was suspended about 10 cm above the surface of the glass tabletop. A computer-controlled LCD projector was used to project visual targets onto a virtual plane in front of subjects. Targets were projected onto a back-projection screen, suspended 20 cm above the hand, and were reflected into the view of subjects by a semi-silvered mirror positioned 10 cm below the screen. This resulted in the perception of virtual targets floating in the plane of the subject’s hand. A lamp illuminated the area below the mirror, providing subjects with full visual feedback of their arm during the experiment.

Fig. 1A–C Experimental setup and design. A Subjects performed rapid pointing movements in the horizontal plane, to virtual targets projected onto the plane of the hand. A compressed air system supported the arm against gravity and provided for frictionless motion on a glass tabletop. Subjects pointed to a central fixation target with the eyes and the hand and were instructed to “move the eyes and hand as fast as you can” to a peripheral target, located at one of three eccentricities to the left- or right-hand side of the central fixation target. B Peripheral movement targets were located 15°, 30°, or 45° on either side of the central fixation point. C Subjects performed 120 movements in two experimental conditions. In the overlap condition, the central fixation target (FP) remained on throughout the trial. In the gap condition the central fixation target was extinguished 200 ms prior to the appearance of the peripheral target stimulus (S). Horizontal hand position (H), horizontal eye position (E), and EMG signals from arm muscles were recorded.

Experimental tasks

Subjects performed rapid pointing movements to visual targets projected in the horizontal plane. In each trial, subjects were instructed to look at and hold their hand stationary at a central fixation target (see Fig. 1A, B). After maintaining this position with their eyes and hand for a period of time between 1,750 and 2,250 ms (randomized across trials), a single peripheral target appeared, either to the left or right of the central target, and at one of three different eccentricities: 15°, 30°, or 45° (see Fig. 1B). These targets corresponded to hand movement distances of 6 cm, 15 cm, and 30 cm, respectively, to the left and right of the central fixation target. The order of target presentations was randomized for each subject. Instructions to subjects were to “move your eyes and your hand as fast as you can to the target, and hold the final position”. No instruction was given about the order or relative timing of eye