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The role of eye movements in motor sequence learning

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ABSTRACT

An experiment that utilized a 16-element movement sequence was designed to determine the impact of eye movements on sequence learning. The participants were randomly assigned to two experimental groups: a group that was permitted to use eye movements (FREE) and a second group (FIX) that was instructed to fixate on a marker during acquisition (ACQ). A retention test (RET) was designed to provide a measure of learning, and two transfer tests were designed to determine the extent to which eye movements influenced sequence learning. The results demonstrated that both groups decreased the response time to produce the sequence, but the participants in the FREE group performed the sequence more quickly than participants of the FIX group during the ACQ, RET and the two transfer tests. Furthermore, continuous visual control of response execution was reduced over the course of learning. The results of the transfer tests indicated that oculomotor information regarding the sequence can be stored in memory and enhances response production.

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1. Introduction

An understanding of the processes involved in the fluent production of sequential movements, such as daily activities (e.g., speech, handwriting, typing), musical activities (e.g., drumming, playing piano), and sports skills (e.g., skating, golfing, dancing), has been the object of many scientific inquiries (Clegg, DiGirolamo, & Keele, 1998; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Shea, Kovacs, & Panzer, 2011). Theories of learning have proposed that the acquisition (ACQ) of a movement sequence involves different stages of learning. In the initial stage, participants perform actions in a discrete, step-by-step manner by relying on the sensorimotor transformation for each action. Therefore, visual information regarding the locations of the targets must be transformed into information that is suitable for the motor system for each action. During this stage of learning, explicit knowledge related to the visual–spatial information of the sequence appears to be available to consciousness, and the attention requirements to perform the motor actions are high (e.g., Hikosaka et al., 1999; Shea et al., 2011). Later in the learning process, participants are able to perform the actions sequentially without relying on the inefficient step-by-step sensorimotor processes, and performers become faster and more accurate in responding to the stimuli and perform the corresponding movements in a smoother and more fluent way (Bapi, Doya, & Harner, 2000; Hikosaka et al., 1999; Panzer et al., 2009; Verwey & Eikelboom, 2003). At this stage of learning, sequence production primarily relies on motor information, whereas continuous visual control and attention requirements are reduced. In addition, there is evidence from neurophysiological studies that early in practice, the association cortices, where visual–spatial information regarding the sequence is processed, are involved in both sequence learning and eye movement control. Later in practice, the motor cortices are involved in hand movement control (Hikosaka et al., 1999; Miyashita, Rand, Miyachi, & Hikosaka, 1996). For the successful completion of a sequential task, the two neural structures must interact. Hikosaka proposed that practice eventually results in a shift in the reliance on the neural structures specific to visual–spatial processing and oculomotor output control to the structures associated with motor processing.

The existing theoretical schemes are also consistent with the notion that over the course of learning, continuous visual control and the utilization of visual feedback become less important (Elliott, Chua, Pollock, & Lyons, 1995; Schmidt & McCabe, 1976). For example, Sailer, Flanagan, and Johansson (2005) demonstrated that patterns of eye movements, and therefore visual control, differed depending on the stage of learning (Johansson, Westling, Bäckström, & Flanagan, 2001; Marcus, Karatekin, & Markiewicz, 2006; Press & Kilner, 2013). Participants had to perform a bimanual task to move a cursor on a screen toward a target by producing isometric forces and torques with a rigid tool held between the two hands. At the early stage of learning, the participants visually pursued the moving cursor; with additional practice in a later stage of learning, the participants fixated on the target to be reached until the cursor reached the target, thereby producing the so-called predictive visuomotor control (Flanagan & Johansson, 2003; Mrotek & Soechting, 2007). Sailer et al. (2005) suggested that learning leads to a coupling of cursor-eye movements and contributes to the facilitation of a visuomotor mapping between eye and hand movements, which can be used to effectively control the cursor (for an overview, Wolpert, Diedrichsen, & Flanagan, 2011). Similarly, Foerster, Carbone, Koesling, and Schneider (2011) have proposed that a sequence of task-driven saccades is learned, which indicates that early in practice, a visual search process is necessary to locate the target and that with practice, the visual search process gradually decreases. Consequently, with increased practice, the number of saccades is reduced (Foerster et al., 2011). Thus, attempts to determine the relationship between eye movements and sequence learning must also consider the reduction of the number of eye movements when learning a movement sequence.

To assess if oculomotor information is stored in long-term memory, Foerster, Carbone, Koesling, and Schneider (2012) allowed participants to perform a sequential object-manipulation task in different visual context conditions: a ‘lights on’ condition, which allowed visual control, and a ‘lights off’ condition, in which visual control was precluded. Their findings demonstrated that after previous practice in the ‘lights on’ condition, the saccadic paths and the number of fixations were maintained in the dark context condition as if the visual information was still available (Flanagan, Terao, &