Motor imagery-based implicit sequence learning depends on the formation of stimulus-response associations

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ABSTRACT

Implicit sequence learning (ISL) occurs without conscious awareness and is critical for skill acquisition. The extent to which ISL occurs is a function of exposure (i.e., total training time and/or sequence to noise ratio) to a repeated sequence, and thus the cognitive mechanism underlying ISL is the formation of stimulus-response associations. As the majority of ISL studies employ paradigms whereby individuals unknowingly physically practice a repeated sequence, the cognitive mechanism underlying ISL through motor imagery (MI), the mental rehearsal of movement, remains unknown. This study examined the cognitive mechanisms of MI-based ISL by probing the link between exposure and the resultant ISL. Seventy-two participants underwent MI-based practice of an ISL task following randomization to one of four conditions: 4 training blocks with a high (4-High) or low (4-Low) sequence to noise ratio, or 2 training blocks with a high (2-High) or low (2-Low) sequence to noise ratio. Reaction time differences (dRT) and effect sizes between repeated and random sequences assessed the extent of learning. All groups showed a degree of ISL, yet effect sizes indicated a greater degree of learning in groups with higher exposure (4-Low and 4-High). Findings indicate that the extent to which ISL occurs through MI is impacted by manipulations to total training time and the sequence to noise ratio. Overall, we show that the extent of ISL occurring through MI is a function of exposure, indicating that like physical practice, the cognitive mechanisms of MI-based ISL rely on the formation of stimulus response associations.

1. Introduction

Implicit sequence learning (ISL) is a process in which an individual learns a sequence without conscious awareness. Implicit sequence learning has been demonstrated in numerous domains (Destrebecqz & Cleeremans, 2001; Dienes, Broadbent, & Berry, 1991; Jamieson, Vokey, & Mewhort, 2015; Lang, Gapenne, Aubert, & Ferrel-Chapus, 2012; Nissen & Bullemer, 1987; Rohrmeier & Rebuschat, 2012; Sævland & Norman, 2016), including the study of motor learning, where ISL has been shown to be critical for the acquisition of motor skills (Nissen & Bullemer, 1987; Schwarb & Schumacher, 2012; Wilkinson & Shanks, 2004; Willingham, Nissen, & Bullemer, 1989). To investigate the cognitive mechanisms underlying ISL, many studies have employed the serial reaction time task (SRTT; for a review see Schwarb & Schumacher, 2012). In the SRTT, an individual repeatedly practices a seemingly random sequence, comprised of both a perceptual cue (e.g., auditory or visual stimuli) and motor response (e.g., a key press) (Robertson, 2007), in which, unbeknownst to the individual, a repeating sequence is embedded (Schwarb & Schumacher, 2012; Wilkinson & Shanks, 2004). As perceptual-motor learning is facilitated with training, reaction times (RT) to the repeating (but not random) sequences decrease. The implicit nature of learning is demonstrated as the reduction in RT to the repeated sequence occurs despite the fact that participants report not being explicitly aware of the repeating sequence (Nissen & Bullemer, 1987; Robertson, 2007; Schwarb & Schumacher, 2012; Wilkinson & Shanks, 2004; Willingham et al., 1989).

The cognitive mechanism underlying ISL is linked to the formation of stimulus-response associations (Schwarb & Schumacher, 2012), in that modifying total training time and/or the ratio of the repeated sequence to noise (i.e., parameters that influence the formation of stimulus-response associations) impacts the extent to which learning occurs. Specifically, the total number of trials can be increased or decreased during an ISL task (i.e., changing total training time; for examples see Kantak, Mummidisetty, & Stinear, 2012;
Nissen & Bullemer, 1987; Willingham et al., 1989), and/or the number of sequence repetitions relative to random button presses during a training block can be increased or decreased (i.e., changing the ratio of the repeated sequence to noise; for examples see Jiménez, Vaquero, & Lupiáñez, 2006; Kaufman et al., 2010; Sanchez & Reber, 2012). Considered together, total training time and the sequence to noise ratio determines the total number of repetitions performed during training, which we refer to as exposure.

Nissen and Bullemer (1987) first demonstrated that ISL could be detected within a single training block, and further showed that ISL became more robust as total training time increased, as RT to the repeated sequence decreased across subsequent blocks of training. A large body of literature investigating the mechanisms of ISL has since been generated using variations of the SRTT to provide further evidence that, until asymptote is reached, the extent of learning increases with increased training time as shown by a decrease in RT to the repeated vs. random sequences (Destrebecqz & Cleeremans, 2001; Goschke & Bolte, 2012; Kantak et al., 2012; Nissen & Bullemer, 1987; Schwarb & Schumacher, 2012; Wilkinson & Shanks, 2004; Willingham et al., 1989). Further, research has also established that the sequence to noise ratio within a training block also impacts the extent to which learning occurs (Jiménez et al., 2006; Kaufman et al., 2010; Sanchez & Reber, 2012). Using a modified version of the SRTT, in which participants responded at precise times to a seemingly random order of targets moving on the screen, Sanchez and Reber (2012) reduced the sequence to noise ratio by increasing the amount of ‘noise’ or number of random sequences within a training block. Indeed, only weak learning was observed when the sequence to noise ratio was too low. Thus, reducing the sequence to noise ratio (i.e. increasing the amount of noise while maintaining the equivalent training time) is shown to result in decreased learning (Jiménez et al., 2006; Kaufman et al., 2010; Sanchez & Reber, 2012). Using a modified version of the SRTT, it was further shown that the rate of ISL is strongly related to the amount of noise while maintaining the equivalent training time (de 2007). Wohldmann et al. (2007) first demonstrated that ISL could be detected within a single training block, and further showed that ISL became more robust as total training time increased, as RT to the repeated sequence decreased across subsequent blocks of training. A large body of literature investigating the mechanisms of ISL has since been generated using variations of the SRTT to provide further evidence that, until asymptote is reached, the extent of learning increases with increased training time as shown by a decrease in RT to the repeated vs. random sequences (Destrebecqz & Cleeremans, 2001; Goschke & Bolte, 2012). Considered together, total training time and the sequence to noise ratio determines the total number of repetitions performed during training, which we refer to as exposure.

2. Method

2.1. Participants

Seventy-two right-handed subjects (49 females, 23.8 ± 7.2 years) from the local and university community volunteered to participate in the study. Right hand dominance was demonstrated by a score of ≥ 40 on the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were healthy, reported normal hearing, were free of neurological disorders, and each provided written informed consent. Prior to the onset of the study, participants were randomly assigned into one of four groups: 4-High, 4-Low, 2-High, or 2-Low (described below). Prior to beginning the experimental task, all participants verbally confirmed they understood the study instructions. The Dalhousie University research ethics board approved the study.
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