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

Sarah N. Kraeutner[a,b], Theresa C. Gaughan[a,b], Sarah N. Eppler[a,c], Shaun G. Boe[a,b,c,d,*]

[a] Laboratory for Brain Recovery and Function, Dalhousie University, Halifax, Nova Scotia B3H4R1, Canada
[b] Department of Psychology and Neuroscience, Dalhousie University, Halifax, Nova Scotia B3H4R2, Canada
[c] School of Health and Human Performance, Dalhousie University, Halifax, Nova Scotia B3H4R2, Canada
[d] School of Physiotherapy, Dalhousie University, Halifax, Nova Scotia B3H4R2, Canada

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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;

* Corresponding author at: School of Physiotherapy, Dalhousie University, Rm 407, 4th Floor Forrest Building, 5869 University Avenue, PO Box 15000, Halifax, Nova Scotia B3H 4R2, Canada.
E-mail address: s.boe@dal.ca (S.G. Boe).

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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; Schvaneveldt & Gomez, 1998).

While both total training time and the sequence to noise ratio can be manipulated independently to impact the extent of ISL that occurs, it is suggested that the exposure to the repeated sequence during training can be used to predict the resulting ISL (Reber, 2013; Sanchez & Reber, 2012). In the aforementioned study (Sanchez & Reber, 2012), while learning was shown to weaken when the sequence to noise ratio was too low, it was shown that this effect occurred not owing to the introduction of more noise, but because there were too few repetitions of the repeated sequence practiced during training to adequately facilitate the formation of stimulus-response associations. In support of this conclusion, it was further shown that the rate of ISL is strongly related to the logarithm of the number of repetitions of the sequence to which the participant is exposed to during training (Sanchez & Reber, 2012). In other words, it has been shown that the extent of ISL is best predicted by exposure to the repeated sequence during training.

Collectively, this evidence indicates that ISL results from the formation of stimulus-response associations, and the extent to which ISL occurs is a function of exposure to the repeated sequence, which can be modified by manipulating total training time and/or the sequence to noise ratio. Not surprisingly, our understanding of the cognitive mechanisms of ISL comes from studies employing paradigms in which participants physically execute the SRTT, as physical practice is the primary modality used for acquiring or strengthening motor skills. As shown in past literature, motor imagery (MI), the mental rehearsal of motor tasks, has been demonstrated to be effective for improving performance and facilitating skill learning in numerous domains (Jeannerod, 1995; Wulf, Shea, & Lewthwaite, 2010). Specifically, while MI can be performed a number of ways, kinaesthetic imagery (i.e., imagery performed while emphasizing the sensations of the action during imagined performance) is the form of MI proposed to best facilitate basic motor skill learning (Stinear, Byblow, Steyvers, Levin, & Swinnen, 2006). Further, there is evidence to suggest that kinaesthetic imagery, when performed from the first person perspective, is thought to be more 'functionally equivalent' to motor execution than other types of imagery (Callow & Hardy, 2004; Callow, Jiang, Roberts, & Edwards, 2016; Callow, Roberts, Hardy, Jiang, & Edwards, 2013; Holmes & Collins, 2001; Jiang, Edwards, Mullins, & Callow, 2015), and is thus the focus of the current study. To date, a limited number of studies have investigated ISL achieved through MI-based practice, and as such we lack a general understanding of the cognitive mechanisms that underlie ISL occurring through MI-based practice.

Previous research has shown that ISL can be facilitated through MI (Kraeutner, MacKenzie, Westwood & Boe, 2016; Wohldmann, Healy, & Lyle, 2007). Wohldmann et al. (2007) first demonstrated that practicing novel four-digit sequences through MI resulted in improved typing ability without explicit knowledge of the sequences. Further, our past work showed robust ISL resulting from MI-based practice using training parameters previously shown to facilitate ISL through physical practice (Kraeutner, MacKenzie, et al., 2016). In this study, participants engaged in four blocks of training with a high sequence to noise ratio, via either physical practice or MI-based practice. Equal learning was shown between the practice modalities, in that the degree to which RTs to the implicit vs. random sequences of equal length decreased was similar following both forms of practice (Kraeutner, MacKenzie, et al., 2016). While this previous research provides evidence that MI-based practice can drive ISL, we have very little understanding of the cognitive mechanisms underlying MI-based ISL, in particular the relationship between the formation of stimulus-response associations and MI-based ISL has yet to be explored.

Accordingly, the purpose of this research is to examine the cognitive mechanisms of MI-based ISL. By probing the link between exposure and the extent to which ISL occurs, we aim to demonstrate that MI-based ISL, like that of physical practice, depends on the formation of stimulus-response associations. Specifically, our primary objective is to examine the extent to which ISL occurs following reductions in total training time (defined as number of blocks and thus the total number of trials) and the sequence to noise ratio within a training block. It is hypothesized that while learning will occur across all conditions regardless of reductions in exposure to the sequence during training, there will be a difference in the extent of learning that occurs as evidenced through effect sizes observed for each condition.

As a secondary objective, we seek to further explore the extent to which ISL is achieved through MI as a function of exposure. Specifically, as exposure to the repeated sequence during physical practice-based training has been shown to be a predictor of the resultant ISL (Sanchez & Reber, 2012), it is hypothesized that the exposure to the repeated sequence during training (defined as total number of practiced repetitions of the sequence during training) will be strongly related to the resulting RT difference (dRT) between the implicit vs. random sequences. Ultimately, the current research will add to our understanding of the mechanisms underlying ISL occurring via MI-based practice.

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.