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Implicit transfer of spatial structure in visuomotor sequence learning

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ABSTRACT

Implicit learning and transfer in sequence learning are essential in daily life. Here, we investigated the implicit transfer of visuomotor sequences following a spatial transformation. In the two experiments, participants used trial and error to learn a sequence consisting of several button presses, known as the $m \times n$ task (Hikosaka et al., 1995). After this learning session, participants learned another sequence in which the button configuration was spatially transformed in one of the following ways: mirrored, rotated, and random arrangement. Our results showed that even when participants were unaware of the transformation rules, accuracy of transfer session in the mirrored and rotated groups was higher than that in the random group (i.e., implicit transfer occurred). Both those who noticed the transformation rules and those who did not (i.e., explicit and implicit transfer instances, respectively) showed faster performance in the mirrored sequences than in the rotated sequences. Taken together, the present results suggest that people can use their implicit visuomotor knowledge to spatially transform sequences and that implicit transfers are modulated by a transformation cost, similar to that in explicit transfer.

1. Introduction

Implicit learning and transfer of behavioral sequences play a key role in daily life. Movement skills, such as typing, and driving, are essential in modern society, and can be improved through the implicit learning of skills (see reviews for implicit learning; Abrahamse, Jiménez, Verwey, & Clegg, 2010; Perruchet & Pacton, 2006).

1.1. Learning of a higher-order structure

In order to investigate the effects and characteristics of learning and the transfer of sequence learning, several implicit and explicit learning paradigms have been used (e.g., artificial grammar learning [AGL], Reber, 1967; Pothos, 2007; serial reaction time [SRT] task, Nissen & Bullemer, 1987; discrete sequence production [DSP] task, Verwey, 1999; visuomotor button press task [hereafter, called the $m \times n$ task], Hikosaka et al., 1995). Through these experimental paradigms, researchers have investigated how people implicitly or explicitly learn a sequence, and have claimed that people are able to learn not only individual elements, but also chunks, or the higher-order structure, of a sequence.

1.1.1. AGL task

In the AGL task, a finite state language provides some sequences; some are consistent with the finite state language (i.e., grammatical) while the others violate it (i.e., non-grammatical). In one such standard AGL paradigm (e.g., Reber, 1967), participants were asked to observe a subset of grammatical sequences in a training phase without any information regarding finite state languages. In a subsequent session, they were required to discriminate between novel grammatical and non-grammatical sequences. The results demonstrated that participants could discriminate the sequences with a level higher than chance.

Research has also suggested that people can successfully discriminate between grammatical and non-grammatical strings even if the surface structure of test sequences looks different to that of trained sequences (e.g., Brooks & Vokey, 1991; Howard & Ballas, 1980; Manza & Reber, 1997; Mathews et al., 1989). For example, let us say that training sequences consist of T, V, J, and X and test sequences consist of B, C, W, and K. People are able to choose as if they knew whether the test strings being shown share abstract structures with trained sequences, which indicates that people learn not only appearance-specific strings, but also abstract codes. Furthermore, some studies have demonstrated that people implicitly learn fragments or chunks of two, three, or four letters (Perruchet & Pacteau, 1990; Servan-Schreiber & Anderson, 1990).

1.1.2. SRT task

A standard SRT task involves horizontally aligned stimulus locations, and participants need to respond to successively presented stimuli by

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means of spatially compatible key presses as quickly and accurately as possible (Nissen & Bullemer, 1987). They are not informed that a specific sequence composed of 10 key presses (typically 8–12 key presses) is repeated during the experiment. In this scenario, reaction times tend to progressively decrease with practice and are faster than those in random sequences presented abruptly, indicating implicit learning of the practiced sequence.

Some studies have demonstrated that transfer can occur between sequences requiring different arm or finger movements, suggesting that abstract representations may underlie sequence production (e.g., Cohen, Ivry, & Keele, 1990; Keele, Cohen, & Ivry, 1990). This implies that some representations used for motor execution are independent of the effectors producing the action. For example, Cohen et al. (1990) found that transfer of speed occurred when participants learned a tapping task using the index, middle, and ring fingers, followed by the same tapping task using only their index fingers (they were unaware that the learning and transfer tasks were identical sequences). Stadler and Neely (1997) also found that the structure of a sequence has a larger influence on learning than does its length. That is, some structures are easier to learn than others (see also Cohen et al., 1990).

1.1.3. DSP task

Similarly with the SRT task, the DSP task also involves horizontally aligned stimulus locations. Participants respond to successively presented stimuli by means of spatially compatible key presses as quickly and accurately as possible (typically 3–7 stimuli, and shorter than the usual length in the SRT task) and repeat the response 500–1000 times in order to develop motor chunks (much larger repetitions than those in the SRT task) that can be executed as if it was a single response (e.g., Verwey, 1999). Once motor chunking is established, execution for the chunked sequence can be done without key-specific stimuli (Verwey, 1999, 2010), is unlikely influenced by a secondary task (Verwey, Abrahamse, & De Kleine, 2010), and is faster than unfamiliar sequences even when the chunked sequence and unfamiliar sequences are mixed in a block (Verwey & Abrahamse, 2012; see also Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013).

Verwey and Wright (2004) examined whether execution for the chunked sequences involved effector-dependent and -independent components. In their experiments, half of the participants practiced 5-key sequences with three fingers of one hand while the others did so using three fingers of both hands. Subsequently, in a transfer session, all participants performed the same sequence and two new sequences with two types of hand configurations: three fingers of one hand or both hands. The results showed that reaction times for practiced sequences were faster with the hand configuration used in the practice session than with that which was new to the participants, supporting the idea of effector-dependent learning. Additionally, performances with the unpracticed hand configuration in the practice sequences were faster than those in the new sequence, suggesting effector-independent learning. Similarly, Verwey, Abrahamse, and Jiménez (2009) observed transfer when finger settings were changed between learning and transfer (e.g., left little, ring, and middle fingers and right index, middle, and ring fingers in the learning session and left ring, middle, and index fingers and right middle, ring, and little fingers), but the effects of transfer were smaller than those in Verwey and Wright's study (2004). This difference indicates that effector-dependent learning is more influenced by the hand-based reference frame than particular effectors such as fingers (see also De Kleine & Verwey, 2009).

1.1.4. $m \times n$ task

Hikosaka et al. (1995) devised a sequential button press task called the $m \times n$ task (Fig. 1). The experimental device consists of 16 light-emitting diode (LED) buttons mounted in a 4×4 matrix. Two or three buttons (i.e., dyad or triad) turn on simultaneously (m) and a sequence is composed of several dyads or triads (n). A monkey or human then learns a correct order of button presses by trial and error after obtaining the same sequence several times. Hikosaka et al. (1999) noted that in the $m \times n$ task, the early trial-and-error stage comprised controlled and explicit processes and the late learning stage were automatic and implicit. This task enables us to test a large number of different sequences and simultaneously examine the effects of well-learned sequences on the same participants.

Sakai, Kitaguchi, and Hikosaka (2003) observed that performances became slow and inaccurate when learned clusters were not preserved in transfer, even when the individual elements of the sequence were identical. In another study, Tanaka and Watanabe (2013) modulated the number of simultaneously active buttons in learning and transfer. An example of the arrangement was two buttons turned on simultaneously (i.e., dyad) and 9 dyad patterns prepared in the learning task (i.e., 2×9 task), and three buttons turned on simultaneously (i.e., triad) and 6 patterns of triads prepared in the transfer task (i.e., 3×6 task). In these two sequences, the button-press sequence (i.e., spatial and temporal) remained identical, but the number of buttons shown at the same time was different. Even if participants did not notice that the sequences were identical, implicit transfer occurred. This result indicated that people are able to learn a sequence as a whole, independently of the elements of that sequence, which led to the implicit transfer. Similarly to the SRT studies (Cohen et al., 1990; Keele et al., 1990), studies in the $m \times n$ task have demonstrated that transfer can occur between sequences requiring different arm or finger movements, which suggests that abstract representations underlie sequence production (e.g., Bapi, Doya, & Harner, 2000; Bapi, Miyapuram, Graydon, & Doya, 2006).

1.1.5. Interim summary

Collectively, previous studies using the various experimental paradigms have suggested that people can learn the higher structure of a sequence, as well as learn a sequence independently of the relationship between finger movements and the spatial configuration of button presses. In these studies, transfer paradigms were usually adopted in order to investigate what people learned (or developed) in sequence learning; therefore, revealing what people are able to transfer enables us to discover what people learn in certain tasks (e.g., Schmidt & Young, 1987). Thus, in the aforementioned studies, only one aspect of learning was changed in transfer, which resulted in that either finger movements or spatial button presses remained identical between the learning and transfer tasks. However, few studies have investigated the extent to which people can implicitly transfer their obtained knowledge or skills (i.e., characteristics of implicit transfer), such as in situations involving different finger movements and spatial configurations (i.e., higher-order structure). Thus, in the present study, we sought to investigate implicit transfer of a higher-order structure.

1.2. Transfer of a higher-order structure

Some researchers have reported that people could not only learn an abstract structure of a sequence but also understand a higher-level relationship between learning and transfer (e.g., a sequence in learning is temporally or spatially reversed in transfer; reversed relationship). For example, people implicitly detected reversed or mirrored structures of musical melodies even when they were unaware of the structure (e.g., Dienes, Kuhn, Guo, & Jones, 2012; Dienes & Longuet-Higgins, 2004; see also Kuhn & Dienes, 2005). Dienes and Longuet-Higgins (2004) studied sequences that consisted of twelve musical tones in which the first six tones were randomly generated and the second six tones were altered from the first tones with specific alternations. During the learning phase, participants were told that the musical melody obeyed some specific rules; in the test phase, they were required to answer whether the musical melody had followed the rules or not. Results showed that participants who had background experience with atonal music could implicitly detect altered melodies (e.g., reversals and mirrors). Similarly, Li, Jiang, Guo, Yang, and Dienes (2013) used Chinese tonal symmetries and found that people acquired unconscious