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Novel vibrotactile discrimination task for investigating the neural correlates of short-term learning with fMRI

Kenneth Tang[a,d,1], W. Richard Staines[b,c,d], Sandra E. Black[a,c,d,2], William E. McIlroy[a,b,c,d,*]

[a] *Graduate Department of Rehabilitation Science, University of Toronto, Toronto, Ontario, Canada*
[b] *Department of Kinesiology, University of Waterloo, Waterloo, Ontario, Canada*
[c] *Department of Medicine (Neurology), University of Toronto, Toronto, Ontario, Canada*
[d] *Heart and Stroke Foundation Centre for Stroke Recovery, Sunnybrook Health Sciences Centre, Toronto, Ontario, Canada*

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ABSTRACT

Innovative perceptual-motor learning paradigms applicable for functional magnetic resonance imaging (fMRI) offer much potential for elucidating the specific cortical mechanisms that underpin short-term learning. In this study, a novel, fMRI-compatible, vibrotactile discrimination task, adapted from a tactile version of the Morse-code, was introduced. Uniquely, this task featured distinct components of training and testing, such that cortical changes associated with these modalities of learning may be dissociated. During testing, the ability to correctly associate matching and non-matching vibrotactile/visual stimulus pairs was assessed. Initial testing in naïve healthy subjects ($n = 23$) revealed a training-dependent decrease in discrimination error rates and discrimination reaction time over the course of a single fMRI session. The rate and extent of learning were significantly decreased when the complexity of vibrotactile stimuli to be discriminated was increased. In a subgroup of subjects ($n = 15$) who participated in repeated testing, it was revealed that both initial testing and retesting sessions were characterized by similar within-subject training-related behavioral properties, when different vibrotactile patterns of similar challenge level were presented for the retesting session. Preliminary functional imaging data from a single subject case-study revealed task-related cortical activations over a widely distributed frontoparietal network, which demonstrated spatial consistency within- and also between-sessions (test–retest). Observed behavioral and cortical properties suggest that the current methodology may be suitable for assessing neural changes linked to short-term vibrotactile learning. In addition, demonstrated test–retest capability of the proposed task may uniquely permit applications where test conditions are to be manipulated within-subjects.

1. Introduction

There is much current interest in the elucidation of the cortical mechanisms associated with perceptual-motor learning. Much of our recent understanding has been derived from innovative applications of neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), to learning paradigms that engage various modalities within the perceptual-motor system. With high spatial specificity, fMRI techniques are generally considered to offer a distinct advantage when assessing region-specific cortical effects. In the tactile domain for example, cumulative evidence suggests that tactile learning, even in the short-term, can be directly linked to measurable cortical changes (Hodzic et al., 2004; Pleger et al., 2001, 2003). It is proposed that an improved understanding of the neural mechanisms that underpin short-term (single session over minutes/hours) learning could provide an important foundation for understanding the effects of learning cumulated over the long-term (multiple sessions over days). Approaches well suited for investigating short-term learning-related mechanisms remain not widely available due to the challenge of overcoming various methodologic constraints associated with functional imaging.

It is proposed that an ideal task for investigating stage-dependent effects of learning within the short-term might feature the following elements. First, within-subject early-to-advanced level of task proficiency would be achieved within the timeframe of a single fMRI session (~45 min), such that ongoing cortical changes associated with different stages of learning could be assessed over

* Corresponding author at: Faculty of Applied Health Sciences, Department of Kinesiology, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1. Tel.: +1 519 888 4567x38109; fax: +1 519 885 4070.
E-mail address: wmcilroy@uwaterloo.ca (W.E. McIlroy).
[1] Graduate Department of Rehabilitation Science, University of Toronto, 500 University Avenue, 10th Floor, Toronto, Ontario, Canada M5G 1V7.
[2] Sunnybrook Health Sciences Centre, 2075 Bayview Ave, Suite A4 21, Toronto, Ontario, Canada M4N 3M5.

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a single scan. Second, the ability to partition the task into discrete “*training*” and “*testing*” elements, such that unique cortical mechanisms associated with these modalities could be separately assessed and potentially disentangled. And third, the versatility to alter the challenge level of the task, such that task demands could be adjusted for individuals of various abilities (e.g. individuals with or without specific perceptual-motor deficits). And finally, it would also be useful to have a task that exhibits behavioral test–retest stability (i.e. learning indices could be preserved over multiple retesting) to permit investigations where test conditions may be manipulated within-subjects.

In this study, we investigated whether a novel vibrotactile discrimination task could be adapted into a short-term learning model that features the above methodologic properties, and whether such learning-related changes could be measurable using fMRI. The proposed task uniquely features an adaptation of the Morse-code into specific vibrotactile patterns, thus the ability to discriminate between various vibrotactile patterns (identified by visual letters) provided the key component of the task. Initial testing in healthy control subjects was evaluated to establish behavioral indices of short-term vibrotactile learning. The change in discrimination performance within a single fMRI session, the influence of varying task challenge on the resulting learning indices, as well as the within-subject test–retest stability of the task, were specifically investigated. We hypothesized that subjects would demonstrate training-dependent improvements in behavioral performance over the course of learning, measured by increased discrimination accuracy and decreased reaction time. Secondly, we hypothesized that subjects would demonstrate different rate and extent of learning associated with task-challenge (*easy* vs. *hard* patterns to be discriminated). Thirdly, we also hypothesized that these behavioral properties would be preserved between test–retest sessions within-subjects, so long as unique vibrotactile patterns to be learned were introduced for each session. Finally, a preliminary single-case fMRI investigation with this paradigm was conducted to gain insights into its suitability for future applications aimed at further elucidating the neural basis of short-term learning.

2. Materials and methods

2.1. Subjects

Twenty-three right-handed, healthy adults (11 men, 12 women, age range 22–45) participated in the study. A subset of these subjects ($n = 15$, 6 men, 9 women) participated a second time on a separate day, for test–retest evaluation of the learning task. One male subject from this subset was imaged while performing the task on both occasions (i.e. two separate fMRI scanning sessions), after eligibility for safe MR participation had been confirmed. This study was approved by the ethics review board of the Sunnybrook Health Sciences Centre in Toronto, Ontario, Canada.

2.2. Vibrotactile discrimination task—stimulus and response

Vibrotactile stimuli: A custom-built, fMRI-compatible magnetomechanical vibrotactile device (MVD) (Graham et al., 2001) with a tactile hammer was used to present standardized Morse-code stimuli to the volar surface of the left distal phalanx of the second digit. This type of device is ideal because of its ability to deliver consistent computer-controlled somatosensory stimuli in a magnetic environment. Furthermore, it has been demonstrated that the use of MVDs (Graham et al., 2001; Nelson et al., 2004) can easily generate robust, reliable brain activations for experimentation to investigate activity within the somatosensory and other functionally related brain regions, such as those involved in attention or learning. To control the movement of the tactile hammer, a custom program (LabVIEW software, National Instruments, Austin, TX, USA) was used to initially generate specific stimulus waveforms, which were converted to an analog signal (DAQ1200, National Instruments, Texas, USA), then subsequently amplified (3BST amplifier, Bryston, Canada). Individual waveforms consisted of multiple vibrotactile stimuli of short or long durations delivered at constant amplitude (2 mA), which correspond to the *dot* (·) (duration = 250 ms) and *dash* (–) (duration = 750 ms) elements of a typical Morse-code, respectively. These elements were delivered with a constant inter-element duration of 125 ms. Specific combinations of *dots* and *dashes* were organized to represent unique Morse-code patterns to be discriminated for this study (Table 1).

Table 1
Specific Morse-code patterns (delivered as vibrotactile stimuli) and their unique identifier (letters) adapted for this study. Vibrotactile patterns were composed of random combinations of dot (·) (*short* duration = 250 ms) and dash (–) (*long* duration = 750 ms) elements. These elements were delivered with a constant inter-element duration of 125 ms.

‘Easy’ patterns		‘Hard’ patterns					
H	· · · ·	Q	– – · –	L	· – · ·	T	· – · –
O	– – –	P	· – – ·	E	· · – –	F	· · – ·

Visual stimuli: Individual English letters served as specific identifiers for each vibrotactile (Morse-code) pattern (Table 1), and also as the visual stimuli for the associative learning task. These letters was individually displayed on a visible projection screen, in synchrony with the onset of vibrotactile stimulus delivery, as programmed through a custom LabVIEW program.

Motor response: To acquire behavioral measures as indicators of learning, subjects were provided with a plastic device equipped with two force-sensing resistors (FSRs) separately linked to the second and third digits of their right hand, such that the digits were positioned to provide motor responses by applying a small amount of finger flexion force onto either one of two FSR pads. This setup permitted the subject to indicate a *match* (second digit) or *no match* (third digit) response during the *testing* component of the experiment.

2.3. Manipulation of discrimination difficulty

Without any previously established indications of discrimination difficulty, individual vibrotactile patterns were subjectively classified as *easy* or *hard* initially depending on the apparent complexity of the characteristics of the pattern itself (Table 1), which were subsequently verified on the basis of the resulting behavioral performance (see Section 4). Two specific four-letter sets, each consisting of one *easy* and three *hard* letters, were pre-selected for the study (H–Q–L–T and O–P–E–F). The 1:3 easy/hard letter ratio was specifically chosen to maximize discrimination challenge within each four-letter set. The inclusion of at least one *easy* item within each set was needed for constructing testing items with varying degrees of challenge. The subset of subjects who participated in test–retest sessions learned both sets of letters (randomly ordered) over different days to minimize learning interference. No subjects enrolled in this study had any prior experience with the Morse-code.

3. Experimental design

A unique focus of the present work was the development of a task consisting of a *training* element as well as the conventional component of *testing*. The proposed partition of *training* and *testing* periods was specifically designed to permit separate investigations of cortical changes associated with these specific modalities of learning (i.e. changes between successive periods of *training* and