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Effect of Dual Tasking on Vibrotactile Feedback Guided Reaching – a Pilot Study

Valay A Shah^{1,2}, Nicoletta Risi⁴, Giulia Ballardini², Leigh A Mrotek¹, Maura Casadio^{1,2}, and Robert A Scheidt^{1,3,5,6}

¹Dept Biomedical Engineering, Marquette University, Milwaukee, WI, USA ²DIBRIS, University of Genoa, Genoa, Italy ³Feinberg School of Medicine, Northwestern University, Chicago, IL, USA

⁴Institute of Neuroinformatics, University of Zurich and ETH Zurich, Zurich, Switzerland ⁵Medical College of Wisconsin, Milwaukee, WI, USA ⁶Div. of Civil, Mechanical and Manufacturing Innovation, National Science Foundation, USA

Abstract

Vibrotactile feedback (VTF) has been proposed as a non-invasive way to augment impaired or lost kinesthetic feedback in certain patient populations, thereby enhancing the real-time control of purposeful limb movements and quality of life. We used a dual tasking scenario to investigate the effects of cognitive load and short-term VTF training on VTF-guided reaching. Participants grasped the handle of a planar manipulandum with one hand and received VTF of its motion via a vibrotactile display attached to the non-moving arm. We asked participants to simultaneously perform VTF-guided reaching and a choice reaction time task both before and after training with VTF-guided reaching. Participants readily used VTF to guide goal-directed hand movements in the absence of visual feedback in the dual-task setting, even prior to training. This capability came at the cost of increased movement completion time. Short-term training on VTF-guided reaching induced significant improvements in target capture errors. Pre- and post-training comparisons of dual-task performance found training-related improvements in VTF-guided reach accuracy were resistant to dual-task interference. We found no training-related improvements in movement completion time or button press performance. These results indicate that VTF can be used to complete goal-directed reaches in a dual task situation, and that a single short bout of training sufficed for participants to begin the transition between the cognitive and associative phases of learning for the integration of VTF into the planning and ongoing control of reaching movements.

Keywords

sensory augmentation; vibrotactile feedback; dual task; cognitive load

1. Introduction

Body machine interfaces (BMI) establish bidirectional information transfer between devices and their users [1]. Vibrotactile feedback (VTF) is a popular choice for non-invasive informational displays for many BMIs. These displays do not load visual attention and they can be implemented inexpensively. Vibrotactile feedback has previously been used with BMIs to replace lost sensation or to augment intact sensory modalities such as sight [2, 3, 4], balance [5, 6], and proprioception [7, 8]. Lam et al. [9] and Kapur et al [10, 11] have investigated vibrotactile technologies for post-stroke motor rehabilitation. Lam et al. showed that cued activation of specific elbow and shoulder muscles can improve upper extremity motor control in this population. Leiberman et al. [12] developed a wearable device that provided VTF to multiple locations on the hand, arm, and torso. They asked people to use this device to learn a new motor skill, and their results show that upper extremity motor skill acquisition can improve with VTF in naïve users. However, these prior applications of VTF all conveyed information about performance using error feedback. Error feedback is difficult to implement as it requires timely estimation of the user's intent, and the translation of that intent into signals that can be used to drive the user's behavior toward some goal. By contrast, it is also possible to encode information about limb state in a way that is not referenced to some desired movement pattern (e.g., by encoding hand position, joint angular position, or velocity using off-the shelf sensor technologies) [13].

Recently, Risi and colleagues have demonstrated that limb-state VTF can be used effectively to provide real-time feedback such that movement accuracy in neurologically intact individuals improves beyond limits imposed by intrinsic proprioceptive uncertainty [14]. Risi et al. also showed that over the course of two days of VTF-guided reach training, target capture accuracy further improved toward the limits of vibrotactile perception, even though that level of accuracy exceeded the level attainable using proprioceptive control alone [14]. Successful use of VTF requires the user to sense vibration, decode the information it contains, and produce a task-appropriate response [15, 16]. Given that VTF-guided reaching in Risi et al. took approximately 2.5 times longer to perform than movements without VTF [14], it is likely that the use of online VTF to plan and control movements imposes additional cognitive loads sufficient to degrade movement timing. Thus, using real-time VTF to assist in performing simultaneous tasks, such as reaching for a glass of water while reading or talking, may be difficult until the use of VTF becomes automatic.

We investigated the ability of neurologically intact participants to dual-task VTF-guided reaching while performing a secondary choice reaction time task. We sought to understand if divided attention negatively affects performance of VTF-guided reaching, and to investigate if short-term training with VTF can reduce the negative impact of simultaneous VTF-guided reaching and secondary task performance. We also sought to investigate the extent to which VTF-guided reaching can move beyond the first stage of motor learning [17] within a single session of training, and whether any performance enhancement transfers to the dual-task condition. We hypothesized that performance benefits provided by short-term training with limb state VTF are not susceptible to interference by dual-tasking. Our results indicate that healthy participants are indeed able to use VTF to guide goal-directed reaching in a dual-

task situation and suggest that performance of VTF-guided reaching is robust against dual-task interference.

2. Methods

2.1. Participants

Eleven neurologically-intact participants (7 female) ranging in age from 23-27 years ($24.63 \text{ yr} \pm 1.15 \text{ yr}$), with no known tactile or cognitive deficits were recruited from the University of Genoa community (Genoa, Italy). Ten participants self-reported as right-hand dominant and one participant reported as left hand dominant. Ten of the 11 participants were naïve to the use of vibrotactile feedback for movement control and all were naïve to the experimental objectives. In accord with the 1964 Declaration of Helsinki, all participants volunteered for the study, and all provided written consent to the experimental procedures, which were approved by local Institutional Review Boards serving the University of Genoa (ASL3 Genovese) and Marquette University.

2.2. General Procedures

Each participant completed a single experimental session, lasting approximately 90 minutes. Participants grasped the handle of a custom, planar manipulandum (Fig 1, left panel) and made reaching movements in the horizontal plane with their dominant hand (Reach Task; described below). The manipulandum has a parallel structure and its handle position is determined by the output of two potentiometers (Vishay Intertechnology Inc, Model # 132-0-202) [18]. A computer screen (23.6" Samsung B2430L) was located directly in front of the participant and was used to display a grid of 25 reach targets and a cursor, which corresponded to the instantaneous position of the manipulandum's handle (Fig 2). Subjects rested their non-dominant arm on a rigid support structure with the index, middle and ring fingers resting gently above the numeric keys of a standard computer keyboard. Three of the keys were used to record subject responses during a secondary choice reaction time task (Button Press Task; described below). The manipulandum and dominant arm were blocked from view. Subjects wore noise-cancelling headphones to minimize auditory cues during the experimental tasks.

Visual and Vibrotactile Displays.—Visual stimuli were created in PsychToolbox (MatLab 2017a). Reach targets (5 mm diameter circles) were arranged in a 5×5 grid on the computer screen (Fig 1, right panel), with corresponding nearest-neighbor distances on the screen equal to 2.85 cm along both cardinal axes (i.e. along the horizontal and vertical axes of the screen and along the frontal and transverse axes of hand motion). Note that this inter-target distance is approximately equal to the range of uncertainty within proprioceptive perception of limb position ($2.5 \pm 0.2 \text{ cm}$), as derived using joint angular uncertainty values reported by Fuentes and colleagues [19].

A vibrotactile display was attached to the non-dominant (stationary) arm as described by Krueger et al. [13] (Fig 1, right panel). The display was comprised of four miniature, eccentric-rotating-mass ERM “tactors” (Precision Microdrives Ltd, Model # 310-117), attached to the arm at four locations. Over their operational range, the tactors have

monotonic relationships between activation voltage and both vibration frequency and vibration amplitude such that vibration frequency and amplitude are coupled [20]. The tactors were powered and controlled from a customized microcontroller circuit that interfaced to the Matlab computing environment (version 2017a; the MathWorks Inc.) using the Matlab Arduino Support Package. When activated in the current study, the tactors operated between 60 Hz to 250 Hz. At their peak vibration frequency, the tactors produce a peak vibrational amplitude of 2.8 G, which corresponds to maximal forearm-plus-hand accelerations ranging between 0.53 m/s^2 and 0.77 m/s^2 , depending on participant anthropometrics [13].

We calibrated the vibrotactile display such that a hand displacement of 1.11 cm (i.e., a little less than half of the distance between adjacent targets) corresponded to a change in tactor frequency of 33 Hz. The origin of the vibrotactile display was set to the center of the grid (VTF was set to 0 Hz). To overcome internal friction within the motors, tactor excitation increased discontinuously from 0 Hz to 60 Hz when the hand moved 0.6 mm from the center of the origin. Tactor excitation increased linearly with displacement such that vibration frequency was about 175 Hz at one target distance from the center and 230 Hz at two target distances from the center. If the cursor moved outside of the grid by 0.5 cm, VTF increased to its maximum frequency ($>250 \text{ Hz}$); participants were informed that maximum vibration was only reached when they had left the desired workspace. Near the middle of their operating range, the tactors elicit vibrotactile sensations that depend on which dermatome was stimulated, with dermatome C7 on the lateral forearm being the most sensitive to changes in tactor frequency (a just noticeable difference JND of 33 Hz), and dermatome T1 on the medial forearm being the least sensitive (with a JND of 43 Hz) [21, 22]. In any case, participants needed to move at least two vibrotactile JNDs to reach from one target to an adjacent target under the guidance of VTF.

2.3. Task Procedures

Trial Blocks.—During the session, participants completed a total of 12 blocks of 25 trials each (Table 1). Blocks 1-3 familiarized the subjects to the workspace, the individual reaching and choice reaction time tasks, and allowed assessment of baseline performance in both tasks without VTF. Block 4 familiarized subjects to VTF-guided reaching by providing also visual feedback of cursor motion. Block 5 allowed assessment of pre-training dual task performance in the absence of visual cursor feedback. Blocks 6-10 consisted of VTF-guided reach training. Blocks 11 and 12 allowed for assessment of post-training dual task and reach performance. Participants were allowed a five-minute rest before and after VTF training in Blocks 6-10. Table 1 shows the task and feedback condition of each block. All participants completed the blocks in the same order. Because the focus of this study was on the impact of VTF practice on dual-task performance, and because it was imperative to compare pre- and post-training dual-task performances without intervening experiences unrelated to training, we did not counterbalance the presentation order of Blocks 11 and 12 across subjects.

Reach Task.—Participants were instructed to reach to the visual target as soon as it appeared on screen. After moving, participants verbally indicated they had reached the target. Participants were then given visual cursor feedback and were instructed to correct any

target capture errors so that the next trial could start. During movement, participants could be provided with one of four combinations of visual and VTF feedback of hand position: (i) only visual feedback of the cursor (V+ T-); (ii) only VTF (V-T+); (iii) both forms of feedback (V+T+); (iv) no feedback, i.e., neither visual feedback of the cursor nor VTF (V-T-).

Button Press Task.—In this choice reaction time task, participants were instructed to press 1 of 3 color-coded keys when they saw a colored target change shape. The target could be 1 of 3 colors: red, blue, or green. The target first appeared as a hollow ring. After a variable amount of time (350ms to 850ms), the target switched from a hollow ring to a filled circle of the same color, cueing the participant to press the corresponding button; the target did not move.

Dual Task.—During this task, participants completed the Reach Task and the Button Press Task simultaneously. Changes in target location were used to cue dominant hand movements as in the reach task. Changes in a colored target's shape were used to cue non-dominant hand key presses as in the button press task. Participants were instructed to begin reaching to the hollowed ring as soon as it appeared, and then press the color-corresponding button when the hollowed ring changed shape into a filled circle.

2.4. Data Acquisition and Statistical Hypothesis Testing

In the Reach Task, we computed target capture error as our primary measure of performance. Target capture error was defined as the Euclidean distance between the actual target location and the final location of the cursor at the end of the movement (Fig 2, magenta lines). We sought to address the hypothesis that performance benefits provided by short-term training with supplemental VTF of hand position information are robust against dual-task interference. We used repeated measures ANOVA and post hoc, one-tailed, paired sampled t-tests to test the statistical significance of changes in capture error between the first and final blocks of training as well as the error of pre and post-training dual tasking. We sought to verify that VTF training would indeed result in improved performance in the reach task. If the beneficial effects of reach training are robust against dual-task interference, we would anticipate that training-dependent improvements in reaching performance would also be evident in the dual task testing condition. Our secondary measure of performance was target capture time, defined as the time difference between reach trial start and participant indication of target capture. We used repeated measures ANOVA with post hoc, one-tailed, paired sampled t-tests to analyze the target capture time (time difference between trial start to participant stating they have reached the target). We expect to see training dependent improvements in target capture time in the dual task testing as well as the first and final blocks of training.

In the Button Press Task, we computed the number of correct button presses in the experimental blocks wherein this task was performed (Blocks 5, 11). Based on the Capacity Sharing Model [23], we anticipated that reduced interference due to training-related improvements in reach performance might result in better Button Press Task performance.

Here, we used a one tailed, paired samples t-test to evaluate the statistical significance of changes in the percentage of correct responses pre- to post-training.

3. Results

In this study, participants grasped the handle of an instrumented manipulandum with their dominant hand and practiced performing a horizontal planar Reaching Task guided by vibrotactile stimuli that encoded real-time information about the location of the moving hand. We hypothesized that performance benefits provided by short-term training with supplemental vibrotactile feedback would be robust against interference by a secondary choice reaction task that increased cognitive loading. All subjects were attentive throughout their experimental sessions and all were able to understand and complete each task. Using separate one-way repeated measures ANOVA, we found significant differences in reaching error ($F_{(8,80)} = 2.89$, $p < 0.05$) and target capture time ($F_{(8,80)} = 3.94$, $p < 0.05$) across reaching trial Blocks 2 through 11. Post-hoc analyses exploring these main effects are discussed in the following paragraphs.

3.1. Reach Task

Baseline Performance (single task).—With visual feedback of the cursor but no vibrotactile feedback (Fig 3, Block 1; V+T–), reaching error was minimal at 0.12 ± 0.01 cm (mean $\pm$ SEM) and subjects required 1.99 ± 0.14 s to complete the reach. In the absence of both visual and vibrotactile feedback, target capture error averaged 2.25 ± 0.16 cm and target capture time was 2.50 ± 0.25 s (Block 2; V–T–). Thus, upon removing visual feedback of performance (V–T–), movement accuracy degraded greatly relative to the baseline V+ feedback condition ($t_{10} = 13.76$, $p < 0.05$) and movements required a longer amount of time ($t_{10} = 3.53$, $p < 0.05$).

Immediate Effects of Vibrotactile Feedback Training.—Participants improved their reach accuracy over a short period of training, involving only 125 movements spanning approximately 30 minutes. Target capture error in the first block of VTF training (Block 6) averaged 2.09 ± 0.14 cm, whereas error in the last block of VTF training (Block 10) averaged 1.76 ± 0.14 cm. By the end of training, target capture errors approached the limit of performance expected from projecting an estimate of vibrotactile sensory acuity in the arm, as described by our earlier work [21], onto the plane of hand movement. Across participants, we found the decrease in target capture error from the start to end of training to be statistically significant ($t_{10} = 3.04$, $p < 0.05$). However, mean target capture time at the beginning of training (5.84 ± 1.75 s, Block 6) did not significantly differ ($t_{10} = 0.801$, $p > 0.05$) the end of training (4.93 ± 1.08 s, Block 10).

Effects of Vibrotactile Feedback Training on Dual Task Reach Performance.—

Consistent with a transition from the cognitive phase of motor learning to the associative phase [17], we found that the learning achieved through VTF training in the simple reaching task was transferred to the dual-task condition. Whereas target capture errors in the pre-training dual-task averaged 2.22 ± 0.18 cm (Block 5), errors in the post-training dual-task averaged 1.89 ± 0.14 cm (Block 11). This change reflects a significant decrease in target

capture error as a result of VTF training in the simple reach task ($t_{10} = 2.44$, $p < 0.05$). By contrast, a comparison of mean target capture time pre-training (Block 5: 4.91 ± 1.00 s) vs. post-training (Block 11: 4.52 ± 0.84 s) did not find a significant decrease ($t_{10} = 0.62$, $p > 0.05$), suggesting that the use of VTF had not yet moved beyond the associative phase toward automaticity.

3.2. Button Press Task

We also examined participants' performance of the Button Press Task during pre- and post-training dual-task. Prior to training, participants pressed the correct button $93.6 \pm 2.1\%$ of trials. After training, participants continued to perform at a similar rate of success ($97.0 \pm 0.8\%$ of trials). Participants did not show any improvement in the untrained secondary task ($t_{10} = 1.93$, $p > 0.05$ after Bonferroni correction), demonstrating that training effects due to reach training with VTF were specific to the trained task.

4. Discussion

This study tested the extent to which reductions in target capture error resist dual-task interference from a choice reaction task that increased cognitive load. Our results indicate that healthy participants can indeed use VTF to complete goal-directed reaches in a dual-task situation, and that training-dependent performance gains are preserved while performing a simultaneous cognitively demanding task. We also observed no aftereffects of VTF-guided reach training when VTF was removed. Therefore, the performance improvements reported here were due specifically to the real-time use of VTF for ongoing control of reaching, rather than a general performance improvement due to, for example, improved calibration of proprioceptive sensation.

We also found that VTF-guided reaching required increased target capture time. This finding was consistent across all trial blocks involving VTF. In contrast to the training-induced improvements in the target capture error, we found no significant improvements in the target capture time after VTF-guided reach training. Taken together, these findings demonstrate that participants began to transition between the cognitive and associative phases of learning [17] within a single short bout of training on the VTF-guided reaching task.

By contrast, performance on the Button Press Task did not improve following reach training, suggesting that training-dependent improvement in reach performance did not result from increased automaticity of vibrotactile control during reaching. We base this conclusion on the Capacity Sharing Model of attentional resources [23], which states that attention is a finite resource shared across tasks, and that if two or more tasks are performed simultaneously, each task can access less attentional capacity than if it were performed individually, which can lead to degraded performance. If training-dependent improvement in reach performance did originate from increased automaticity of control, we would have expected the Button Press Task the gain access to additional attentional capacity released by the automatization of VTF-guided reaching, thus leading to improved accuracy of button pressing. Because we observed no improvement in performance of the secondary task, we conclude that a short bout of VTF training did not reduce the attentional resources required by VTF-guided reaching.

Vibrotactile feedback was easy to learn in the sense that our subjects were not told how the vibration frequency encoded their movements, yet within one training session (125 trials) they were able to improve their ability to use VTF to reach accurately. Thus, our participants learned to use novel information (vibrotactile feedback) to complete a goal-directed reaching task, with ease and without explicit instruction, in the absence of visual feedback. Intuitiveness and automaticity are important when considering the use of VTF for sensory augmentation or substitution especially for individuals with somatosensory impairment on a portion of their body (e.g., some stroke survivors), who may also present with cognitive deficits that can reduce their ability to correctly interpret novel sensory stimuli and integrate them into the ongoing control of movement. In this study, we have shown that within a single day of training, participants experience motor learning through parts of the cognitive and associative stages but have not yet reached the autonomous stage [17]. Future studies should repeat the current study with participation in a long-term VTF-based training program to determine the extent to which VTF-guided reaching can become autonomous with training, thereby enabling improved dual-task performance on secondary tasks requiring visual attention or other forms of cognitive load.

Because vibration frequency and amplitude are coupled in the ERM tactors used in this study, our vibrotactile display is limited in the way it can encode information about the moving limb. We cannot, for example, encode independent X- and Y-axis motions along the coupled dimensions of vibration frequency and amplitude, nor could we use frequency and amplitude of vibration to encode hand position and velocity, respectively. This is not a concern in the present study because we used separate vibrotactile channels to encode hand position along X- and Y-axis motions within a Cartesian reference frame centered on the target workspace. This choice of reference frame was one of convenience, due to our use of the planar manipulandum to track hand motion. Future studies should explore other limb state encoding schemes that might be more easily implemented using existing wearable motion sensors, as well as the kinematic and cognitive impact of adding additional channels to the vibrotactile display to simultaneously encode, for example, the 3D position of the hand and grasp force.

5. Conclusions

This pilot study investigated the extent to which the learned ability to use VTF to guide reaching is impacted by simultaneous performance of a secondary task. We found that VTF training can induce performance improvements of reaching but did not improve performance of a choice reaction time task. The improvements in reaching error during dual-tasking indicates that VTF can be used while multi-tasking. Due to the efficacy of the short training bout described here, we conclude that a single short bout of training sufficed for participants to begin the transition between the cognitive and associative phases of learning for the integration of VTF into the planning and ongoing control of reaching movements. Future studies should explore the impact of long-term (multi-day) training on the accuracy, stability, and automaticity of VTF-guided reaching.

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Fig. 1.

Experimental set up. Left Panel: Participants sat in front of a computer screen that displayed targets and a cursor. Cursor location was controlled via the manipulandum held in the participant's right hand. Central Panel: A vibrotactile display consisting of four vibrotactile motors was placed on the participant's non-dominant left arm. Right Panel: The Y+ tactor was activated when the cursor/hand was in the hemi-space above the center row of targets, whereas the X+ tactor was activated when the cursor/hand was to the right of the center column of targets. The participant also used the non-dominant hand to make key presses corresponding to the color of the target during the dual task trials. The manipulandum and the dominant arm were blocked for the participant's view, although the occlusion screen is not shown here to facilitate visualization of the setup.

Fig. 2.

Task workspace showing sample reaching trajectories from one participant. Twenty-five black circles depict the workspace and possible target locations. Green circle: start location; red circle: the goal target (the only visible cue). Thick blue and red lines: unseen trajectories. Magenta stars: the location where the participant indicated (s)he had reached the goal. Thin magenta line: Euclidian reach error.

Fig. 3.

Left: Target capture error magnitude (cm). Right: Target Capture Time (s). Grey bars: reaching only trial blocks that include VTF (T+); White bars: reaching only trial blocks without VTF (T-). Blue bars: dual-task trial blocks that include VTF (T+). V+: concurrent visual feedback; V-: no visual feed-back during movement. Horizontal black lines with endcaps: statistical comparisons that reached significance ($p < 0.05$). Horizontal red lines: the magnitude of movement corresponding to 1 vibrotactile JND for the extremum dermatomes (C7 and T1) under the mapping used to project hand position into the vibrotactile display. ITD indicated the inter-target distance of 2.85 cm. Error bars: mean $\pm$ SEM.

Table 1.

Description of task blocks: number of trials, block type, and feedback condition type.

Block	Trials	Task	Feedback	Type
1	25	Reach	V+T–	Baseline
2	25	Reach	V–T–	Baseline
3	25	Button Press	N/A	Familiarization
4	25	Reach	V+T+	Familiarization
5	25	Dual	V–T+	Pre-Training
6-10	25 each block	Reach	V–T+	Training
11	25	Dual	V–T+	Post-Training
12	25	Reach	V–T–	Post-Training