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Using dual tasks to test immediate transfer of training between naturalistic movements: A proof-of-principle study

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Running head: Testing the transfer of training with dual tasks

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ABSTRACT

Theories of motor learning predict that training a movement reduces the amount of attention needed for its performance (i.e. more automatic). If training one movement transfers, then the amount of attention needed for performing a second movement should also be reduced, as measured under dual task conditions. The purpose of this study was to test whether dual task paradigms are feasible for detecting transfer of training between two naturalistic movements. Immediately following motor training, subjects improved performance of a second untrained movement under both single and dual task conditions. Subjects with no training did not. Improved performance in the untrained movement was likely due to transfer, and suggests that dual tasks may be feasible for detecting transfer between naturalistic actions.

Keywords: motor training; transfer; naturalistic movement; feasibility

INTRODUCTION

The nervous system's ability to transfer learned information from one context to another continues to captivate the fields of neuroscience and psychology. The neural substrates and mechanisms of transfer have been difficult to define and observe, along with its constraints and time course. Nonetheless, the term "transfer" is frequently used both in research and clinical practice. A clearer understanding of what transfer is and how it occurs will advance the development of new hypotheses to be tested and innovative applications to be implemented.

Human motor behavior offers tremendous potential for gaining insight into the process of transfer. The study of human movement has already provided key evidence that learned information is transferrable to novel tasks. Transfer of motor training is broadly defined as the gain (or loss) in the proficiency in one motor task as a result of practice on some other motor task (Schmidt & Lee, 1999). For example, behavioral and computational studies in motor adaptation have quantified the transfer of training by using computer-based experiments to expose subjects to novel conditions of a motor task (Bock, 1992; Bock & Burghoff, 1997; Conditt, Gandolfo, & Mussa-Ivaldi, 1997; Jansen-Osmann, Richter, Konczak, & Kalveram, 2002; Lackner & DiZio, 2005; Shadmehr & Moussavi, 2000). Initial exposure to such conditions typically results in measurable errors that are, over time, minimized with repeated training (Held & Freedman, 1963; Shadmehr & Brashers-Krug, 1997; Stratton, 1897). This is known as motor adaptation, a construct that is different than the ability to transfer what has been adapted to other, separate tasks (Seidler, 2010). If what is adapted through training is transferred, error in a transfer task should be less than if no training had occurred at all. This evidence of such transfer has been documented in a number of visuomotor and dynamic adaptation studies (see above studies). Often, the trained and novel conditions in these studies are variants of a single task. For example,

adaptation to a clockwise 30° rotation of visual feedback during reaching to a target can improve initial naïve performance and accelerate the rate of adaptation to other degrees of rotation (Seidler & Noll, 2008; Sing & Smith, 2010).

To date, motor adaptation studies by and large have used targeted reaching movements in a single plane to probe the processes of motor learning and transfer, in which performance is typically measured in terms of angular or linear distance (i.e. degrees or millimeters). Performance in the trained and untrained contexts is executed in similar extrinsic workspaces (Abeele & Bock, 2003; Bock & Burghoff, 1997; Mattar & Ostry, 2010) or 'state spaces' (Donchin, Francis, & Shadmehr, 2003; Francis, 2008; Huang, Patton, & Mussa-Ivaldi, 2010; Joiner, Ajayi, Sing, & Smith, 2011; Thoroughman & Shadmehr, 2000; Thoroughman & Taylor, 2005), with similar or homologous sets of muscles or joint motions (Boutin et al., 2011; Imamizu & Shimojo, 1995; Stockel & Wang, 2011; Torres-Oviedo & Bastian, 2010; Wang & Sainburg, 2003, 2004), and is measured in the same units (Ahmed & Wolpert, 2009; Bock, Schmitz, & Grigorova, 2008; Goodbody & Wolpert, 1998; Koeneke, Battista, Jancke, & Peters, 2009; Radhakrishnan, Hatzitaki, Vogiannou, & Tzovaras, 2010; Seidler, 2007). Even in these highly constrained conditions that involve some sub-components of functional movement (i.e. point-to-point reaching), findings suggest that when transfer does occur, it is only partial (Abeele & Bock, 2003; Cotti, Guillaume, Alahyane, Pelisson, & Vercher, 2007; Howard, Ingram, & Wolpert, 2010; Ikegami, Hirashima, Taga, & Nozaki, 2010; Krakauer, Pine, Ghilardi, & Ghez, 2000; Lordahl & Archer, 1958; Tomi, Gouko, & Ito, 2008). Given the limited transfer between highly similar, experimental tasks, can transfer be expected between more naturalistic movements that involve many steps and degrees of freedom?

Naturalistic movements are purposeful, multi-step actions, such as lighting a candle or making coffee (Giovannetti, Libon, Buxbaum, & Schwartz, 2002; Hartmann, Goldenberg, Daumuller, & Hermsdorfer, 2005; Leipmann, 1900; Schwartz et al., 1998). If the amount of transfer is dependent on the degree of similarity between tasks (Bills & McTeer, 1932; Deese, 1964; Gagne, Baker, & Foster, 1950; Holyoak & Koh, 1987; Poggio & Bizzi, 2004), then one might expect that little or no transfer would occur between two distinct, naturalistic movements that do not necessarily share common spatiotemporal characteristics. Encouraging results from clinical observations do, however, demonstrate that performance on one task can improve as a result of practicing a different task altogether. Salient evidence of significant transfer between distinct tasks comes from improvement seen on clinical tests of arm and hand function after neurorehabilitation (for examples see Beekhuizen & Field-Fote, 2005; Birkenmeier, Prager, & Lang, 2010; Duncan et al., 2003; Hoffman & Field-Fote, 2010; Page, Sisto, Levine, & McGrath, 2004; Wolf et al., 2006). Following targeted upper-extremity therapies (i.e. constraint-induced or repetitive task-specific therapy), patients often show improvement on various functional tests that systematically measure the ability to move the arm and hand. Patients do not practice the tests or individual test items during the course of therapy, but instead train on self- or therapist-selected motor tasks that often vary substantially from the functional test. For example, patients may practice naturalistic movements like writing, using a fork and spoon, or brushing teeth (Birkenmeier, et al., 2010; Page, et al., 2004). As such, significant and clinically-meaningful improvement on functional tests provides behavioral evidence that training on tasks in therapy is transferrable to performance on different tasks outside of therapy. Though consistent with the broad definition of motor transfer: the gain (or loss) in the proficiency in one motor task as a result of practice on some other motor task (Schmidt & Lee, 1999), these strong clinical findings

appear to be in conflict with the evidence of only partial transfer seen in controlled laboratory experiments when the tasks are quite similar and highly constrained (Bock, 1992; Bock & Burghoff, 1997; Conditt, Gandolfo, & Mussa-Ivaldi, 1997; Jansen-Osmann, Richter, Konczak, & Kalveram, 2002; Lackner & DiZio, 2005; Shadmehr & Moussavi, 2000).

Rationale for novel approach: A 'proof of principle'

One way to address this conflicting evidence would be to study transfer of training in different, naturalistic tasks. Systematically quantifying performance of naturalistic tasks within and between subjects can be challenging in the laboratory. A similar challenge arises when studying transfer: How can transfer be measured? While quantifying transfer between any two tasks or conditions may be difficult, there may be indicators that transfer has occurred (Gagne, Foster, & Crowley, 1948; Stevens, 1951). In this proof of principle study, we propose that changes in dual task performance could serve as an indicator of transfer between two naturalistic tasks that are spatiotemporally distinct. To test this idea, we developed an approach for detecting whether information acquired during training is transferred from one task to another. The rationale for this approach centers on the phases of skill learning model (Fitts & Posner, 1967), which describes how complex skills are acquired across three phases: an early "cognitive" phase, an intermediate "associative" phase, and a final "autonomous" phase. When performing tasks that are novel and unskilled, high levels of attention are necessary. This is characteristic of the cognitive phase (Fitts & Posner, 1967). With practice, less attention is required for task performance until the autonomous phase, in which task performance is automatic. In this autonomous phase, learned tasks can easily be executed simultaneously with other tasks, given that little attention is necessary for performance (Fitts & Posner, 1967).

Given this model of skill learning, the more automatic a given task is, the more it has been learned. A motor task's automaticity is easily tested using a dual task condition (Gopher & Sanders, 1984; Neumann, 1984; Passingham, 1996), such that an automatic task requiring little attention is much less susceptible to interference from a simultaneous second task than a novel, unskilled task. The amount of dual task interference, therefore, can measure a task's automaticity. Automaticity is operationally defined as the ability to perform a skilled movement without conscious or executive control or attention directed toward the movement (Kelly, Eusterbrock, & Shumway-Cook, 2012; Poldrack, Sabb, Foerde, Tom, Asarnow, & Bookheimer, 2005; Wu, Kansaku, & Hallett, 2004). Training on given motor task has been shown to improve that task's automaticity when tested under dual task conditions (for example see Field, Mogg, & Bradley, 2006; Park, Waqar, Kersey, Modi, Ong, & Sleep, 2011; Poldrack, et al., 2005; Smith & Chamberlin, 1992), thereby providing behavioral evidence for the phases of skill learning model (Fitts & Posner, 1967). It remains unclear, however, whether the automaticity of an untrained task can also improve as a result of practicing and learning another task. If so, then such changes in automaticity without training would indicate transfer of learning. With this novel approach for detecting transfer, the trained and untrained motor tasks may but do not necessarily need to share common spatiotemporal characteristics (e.g. muscle activation patterns, joint motions, workspace) and can be executed in a variety of environments (e.g. laboratory, clinic, real-world). The purpose of this study was to demonstrate the feasibility of using dual task paradigms to detect transfer of motor training. We predicted that if training can transfer between two naturalistic motor tasks, then performance of both motor tasks will improve under single and dual task conditions, even though one motor task was not practiced at all. This prediction is consistent with the idea that transfer of motor training can improve the skill or proficiency of an

untrained task (Schmidt & Lee, 1999). To date, dual task paradigms have not been widely used to study transfer despite their ability to reveal processes not readily evident in conventional measures (Bahrick, Noble, & Fitts, 1954).

Criteria for the 'proof of principle'

In order to test whether transfer of training can be examined using a dual task paradigm, three criteria needed to be met. First, there needed to be dual task interference when simultaneously performing each motor task with another nonmotor task prior to training. Second, both motor tasks needed to be under-practiced and not over-learned, such that subjects could show improvement with training. The third and related criterion was that performance and improvement on all tasks needed to be measurable. Performance on each motor task did not, however, need to be measured in the same units or meet the same goal. Because this study was designed to test only the feasibility of this method, rather than its efficacy or validity, training occurred within a single session. Detailed justification for our selection of motor and cognitive tasks, and our particular experimental design, is outlined below in the Materials and Methods. Because this novel approach to investigating transfer does not necessarily require shared movement characteristics among tasks, it has the potential to uncover new information about learning and generalization that current approaches have not had the ability to explore.

MATERIALS AND METHODS

General procedure

This study used a single session, mixed model design to evaluate the transfer of training between two motor tasks: one trained task and one untrained task. For all tasks, subjects sat in a

chair behind a table (76 cm x 51 cm) that was placed at their midline with its closest edge across their mid-thighs. Table height was adjusted to be as low as possible without contacting the thighs. At the beginning of each trial, subjects began with their left hand resting face down on the start position, which was located at the closest edge of the table in line with their left shoulder. Subjects held on to a vertical cylinder with their right hand during each trial, located 7 cm from the closest edge of the table in line with their right shoulder, preventing use of the right hand during either motor task or the auditory tasks (i.e. for stabilizing objects or counting letters). This general setup is displayed in Figure 1A.

Subjects

Twenty-seven neurologically-intact adults (mean±SD age: 27±4.3 years; 24 females, 3 males) participated in this study. All subjects were right-handed based on self-report. Potential subjects were included if they 1) had no known neurological disease or previous head injury, and 2) had no disability or injury affecting their upper extremity on either side. This study was approved by the Washington University Human Research Protection Office, and was conducted in compliance with the Helsinki Declaration. All subjects provided informed consent prior to beginning the study.

Task selection and experimental design

This study used an auditory task that required sustained listening attention, or "vigilance" (Aylward, Brager, & Harper, 2002; Borgaro et al., 2003; Curtindale, Laurie-Rose, Bennett-Murphy, & Hull, 2007; Erickson, Goldinger, & LaPointe, 1996; Seli, Cheyne, Barton, & Smilek, 2011). An auditory vigilance task was selected because of its ecological validity, as sustained

auditory attention is often concurrent with real-world actions (Hubal, Reyes, & Newlin, 2009; Pang et al., 2005; Yantz, Johnson-Greene, Higginson, & Emmerson, 2010). The trained motor task was a simulated feeding task that required spooning beans from one cup to another. The untrained motor task was a simulated dressing task that required fastening buttons sequentially. The motor tasks used in this study were selected because they simulate feeding and dressing respectively (Collin, Wade, Davies, & Horne, 1988; Duncan et al., 1999; Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969; Keith, Granger, Hamilton, & Sherwin, 1987; Taub et al., 1993; Walker & Lincoln, 1990), both of which are relevant and meaningful to one's ability for self-care (Blennerhassett, Carey, & Matyas, 2008; Duncan, Wallace, Studenski, Lai, & Johnson, 2001). Holding a spoon during feeding and manipulating buttons during dressing are typically performed daily with the dominant or "preferred" hand (McCormick, Rath, Patra, Pereira, & Wilkinson, 2008; Oldfield, 1971; Rigal, 1992); thus, the feeding and dressing tasks were presumably well-practiced and not novel for the neurologically-intact subjects in this study when using their dominant hand. Because the motor tasks needed to be under-practiced and not over-learned in order for training to improve performance, all subjects used their nondominant, left hand throughout the entire experiment. Both motor tasks are illustrated in Figure 1B. To determine whether any transfer was attributable to motor training specifically rather than an increase in general arousal level at the post-test session, some subjects performed an untrained nonmotor task rather than the untrained dressing task before and after training with and without simultaneously performing the auditory task. All tasks are described in detail below.

Auditory task

Prior to performing any motor task, all subjects performed two trials of the auditory task. The auditory task required subjects to listen to recordings of 35-letter sequences. Each 35-letter sequence consisted of a random series of the same four letters (A, G, M, and O). The sequence began with the word 'start', followed by 35 letters (at 1.75 Hz, 20-sec duration), and then ended with the word 'stop'. Prior to each sequence, subjects were instructed to pay attention to the number of times a target letter was heard. The target letter was A, G, M, or O, and was changed for each trial. Immediately after each sequence, subjects were asked to verbally report the number of times a target letter was heard. The primary measure of performance for the auditory task was the number of listening errors per trial. The number of listening errors was calculated as the difference between the reported and correct number of times the target letter was heard. This difference was expressed as an absolute value, such that a subject could have a score of one error by either over- or underestimating the number of target letters by one.

All sequences were recorded live using an external microphone (Gigaware Omnidirectional model 33-119, Ignition L.P., Dallas, TX) and played at a comfortable volume through headphones (Sony MDR-V700) via Windows Media Player (version 11, Microsoft Corporation). In general, auditory vigilance tasks are relatively independent of acquired skills such as aptitude and knowledge (Bakan, 1959; Lang & Bastian, 2002; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956).

Trained and untrained motor tasks

The trained motor task was a simulated feeding task that required spooning beans from one cup to another (Fig. 1B, left panel). At the start of each feeding trial, subjects picked up a plastic spoon (weight = 1.8 grams) with their left hand and spooned two beans at a time (kidney,

uncooked) from one cup away from their body to another cup. The start cup contained 40 beans that were distributed evenly across the bottom. The cups (9 cm diameter, 5.5 cm high) were secured to a wooden board 16.5 cm apart (Fig. 1B, left panel), which was centered in line with the subject's left shoulder. Subjects spooned as many beans as possible per trial in the target direction, and the total number of beans in the target cup was recorded after each trial. Subjects were given verbal feedback about the number of beans spooned after each trial. The measure of performance for each trial of simulated feeding was the number of beans spooned.

The untrained motor task was a simulated dressing task that required fastening buttons sequentially. At the start of each dressing trial, subjects began buttoning the top of seven buttons (3 cm diameter) that were sewed 2 cm apart vertically to a piece of plain weave cotton fabric (Fig. 1B, right panel). Both pieces of the fabric were secured to a wooden board, with the placket centered in line with the subject's left shoulder. The button-side of the fabric was folded onto the board, while the button hole-side of the fabric was unfolded onto the table prior to each trial (Fig. 1B). Fabric weight (120 g/m^2) and thread count (78 per cm) were measured according to ASTM Test Methods D3776-96 and D3775-98, respectively (ASTM, 2001a, 2001b). Buttons were fastened through horizontal button holes in a left-over-right order, relative to the subject (Fig. 1B, right panel). Subjects fastened as many consecutive buttons as possible per trial with their left hand. If all seven buttons were fastened in less than 20 seconds, subjects were instructed to completely unfasten each consecutive button in the reverse order until the trial ended. The total number of buttons completely fastened/unfastened was recorded after each trial. Subjects were given verbal feedback about the number of buttons completed after each trial. The measure of performance for each trial of simulated dressing was the number of buttons fastened/unfastened.

For both motor tasks, no instruction or feedback was given about specific movement patterns; thus, subjects used self-selected movement strategies to complete each task. The duration of all trials was 20 seconds, beginning with the word "start" and ending with the word "stop." Single trials of both motor tasks were performed before and after training to establish pre- and post-test performance without a concurrent listening task (i.e. single task condition).

Untrained nonmotor task

The untrained nonmotor task was an associative recognition task. In general, associative recognition depends upon the ability to form new associations between unrelated items (de Chastelaine, Wang, Minton, Muftuler, & Rugg, 2011). For the current study, a pair of pronounceable nonwords (see Balota et al., 2007) beginning with the same letter (e.g. 'blerved' and 'brenes') was displayed in lowercase Arial Bold 32-point font against a black background for two seconds on a computer screen directly in front of the subjects. Each nonword appeared in either red or blue font, and subjects were instructed to remember the pair and color. After the pair of nonwords disappeared, the word "start" briefly appeared at the center of the screen indicating the beginning of the trial, followed by quartets of red or blue nonwords beginning with the same letter appeared. Each nonword was presented in a different location within an invisible 3x2 grid on the screen. Each quartet was displayed for one second, with followed by a blank black screen for one second (interstimulus interval = 1 sec). Subjects were instructed to respond with a key press on a standard computer keyboard after each quartet to indicate whether the memorized pair and color of nonwords in memory were contained in the quartet ("yes" or "no"). Subjects sat with their right hand touching the keyboard throughout the entire trial, and made their responses with their right index or middle finger. Each trial lasted 20 seconds (10

quartets/trial). The measure of performance for each trial of the associative recognition task was the percentage of correct responses (0-100%). Subjects had two brief familiarization trials to practice using their right hand to respond to other nonword stimuli different from those used in the experiment. Single trials of the untrained nonmotor task were performed before and after training to determine pre- and post-test performance with and without the concurrent listening task.

All nonwords were selected from the English Lexicon Project (Balota et al., 2007). All nonwords had no orthographic neighbors, five to seven letters, no more than two syllables, and had high probability of being correctly identified as a nonword in a lexical decision task (probability range = 0.97 to 1). Nonwords have been used previously as items within associative recognition tasks (Badham & Naylor, 2011; Naveh-Benjamin, 2000). In general, associative recognition tasks can improve with extensive practice (hundreds of trials) (Kray & Eppinger, 2006; Rogers & Fisk, 1991; Wexler et al., 1997) and have been shown to activate brain regions within the hippocampus, striatum, frontal cortex, and anterior cingulated areas (Holcomb, 2004; Kumaran & Maguire, 2007; Meltzer & Constable, 2005; Simon, Vaidya, Howard, & Howard, 2011; Wheeler, McAndrews, Sheard, & Rovet, 2011).

Dual task condition

In the dual task condition, subjects performed one of the motor tasks (or the nonmotor associative recognition task) and the auditory task concurrently. During all dual task trials, subjects were instructed to prioritize the auditory task in order to focus attention away from the motor/nonmotor task. This experimental condition was used to test the other tasks' automaticity. Single trials of the dual task condition (listening + feeding, listening + dressing, and/or listening

+ associative recognition) were performed before and after training to establish pre- and post-test dual task performance. Indication of dual task interference was considered as the degradation in performance of at least one task under dual task condition compared to performance by itself (Kinsbourne, 1981; Woollacott & Shumway-Cook, 2002). Single and dual task condition trials were performed in a pseudorandom order.

Experimental protocol

The schedule of the experiment is illustrated in Figure 1C. Subjects were assigned to one of two groups: a training group (n=12) or a no-training group (n=10). After completing the auditory task by itself and establishing pre-test performance, subjects in the training group completed 50 trials (20 sec each) of simulated feeding in a massed practice training session. During the training session, the experimenter verbally encouraged subjects to spoon more beans than the previous trial, and informed subjects when only half of the training session remained (between trials 25 and 26). Immediately following the training session, the training group's post-test performance was evaluated. For the no-training group, the pre- and post-test sessions were separated by 30 minutes, during which subjects sat quietly at the table.

Although the metabolic conditions experienced by the training and no-training groups during seated reaching and quiet sitting, respectively, were estimated to be comparable (Huang, Kram, & Ahmed, 2012; Spadano, Must, Bandini, Dallal, & Dietz, 2003), it is plausible that this single session of motor training could increase one's overall level of arousal during the post-test session. Performance on a wide range of tasks beyond the motor domain may in fact benefit from a generalized effect of increased arousal. To determine whether this single session of motor training provided the training group with any arousal-based advantage unrelated to the motor

domain compared to the no-training group, additional subjects (n=5) also completed 50 trials (20 seconds each) of simulated feeding in a massed practice training session. The experimental schedule was identical to that of the training group shown in Figure 1C, except that instead of performing the dressing task before and after training, these subjects performed the associative recognition task before and after training.

Data analysis

JMP 8.0 (SAS Institute Inc., Carey, NC) was used for all statistical analyses, and our criterion for statistical significance was set at α=0.05. The Shapiro-Wilk test was used to verify normal distribution of each variable. To test the effect of the dual task condition on listening performance, we used a 2x5 mixed model ANOVA with condition (listening only; listening + feeding, pre-test; listening + dressing, pre-test; listening + feeding, post-test; listening + dressing, post-test) as the within-subject factor. Group (training versus no-training) was the between-subjects factor. This analysis determined whether either of the motor tasks interfered with the auditory task during the dual task conditions. A significant main effect of condition was tested post hoc using the Dunnett method, which compared the number of listening errors in the auditory task only with the number of listening errors in each dual task condition. This method tests whether means are different from the mean of a control condition (Dunnett, 1955). For this study, the listening only condition was considered the control condition because it was indicative of subjects' listening ability without divided attention.

To test the effect of training and transfer on motor performance, we used 2x2x2 mixed model ANOVAs with condition (single task versus dual task) and session (pre-test versus post-test) as within-subject factors. Group (training versus no-training) was the between-subjects

factor. Separate ANOVAs were performed for simulated feeding and dressing. These analyses determined whether performance of a motor task (feeding) improved due to a single session of motor training, and whether improvement transferred to the untrained motor task (dressing). For both simulated feeding and dressing, significant interactions between session (pre-test versus post-test) and group (training versus no-training) were tested post hoc using Tukey-Kramer Honestly Significant Different (HSD) tests (Kramer, 1956; Stoline, 1981). Multiple comparisons were accounted for using the Kackar-Harville correction (Kackar & Harville, 1984). Effect sizes were computed using Cohen's *d* formula to indicate the magnitude of differences between groups. To determine the amount of improvement in each motor task, change scores were calculated for each subject as the difference in pre- and post-test performance (post- minus pre-). One sample *t*-tests were then used to determine whether improvements were significantly different from zero. In subjects who performed the untrained associative recognition task in place of the untrained dressing task before and after motor training, we used a 2x2 repeated measures ANOVA with condition (single task versus dual task) and session (pre-test versus post-test) as within-subject factors. This analysis determined whether an untrained nonmotor task would also improve after a single session of motor training due to increases in overall arousal.

RESULTS

We first confirmed the presence of dual task interference when simultaneously performing each motor task with the auditory task, compared to the auditory task alone. We then tested whether the performance of each motor task under single and dual task conditions improved due to training and immediate transfer.

Dual task interference between auditory and motor tasks

Both the training and no-training groups had similar performance on the auditory task across conditions, as indicated by no significant condition x group effect ($F_{4,20}$=0.60; p=.66) nor main group effect ($F_{1,20}$=0.68; p=.41) on the number of listening errors. Subjects typically had less than one error in the listening only condition (Fig. 2). Listening errors increased in the pre-test dual task condition for both feeding and dressing (main effect of condition: $F_{4,20}$=4.86; p<.01; post hoc p<.01 relative to listening only; Cohen's d = 0.77 and 0.90, respectively), yet were not significantly different in the post-test dual task condition relative to the listening only condition for either motor task (feeding: p=.51; dressing: p=.99). These results showed that for both groups, there was significant dual task interference between the auditory and motor tasks in the pre-test but not post-test session.

Effects of training: Performance of simulated feeding under single and dual task conditions

For simulated feeding, subjects in the training group showed improved performance by spooning more beans per trial throughout the session (Fig. 3A). Performance at the end of training was significantly better than performance at the start of training (paired t-test p<.0001; Fig. 3B). The single session of training resulted in improved feeding performance, as indicated by a significant interaction between session and group ($F_{1,20}$=28.10; p<.0001). Post hoc analysis indicated that the training group's performance post-test was significantly better than pre-test (p<.0001; Cohen's d = 2.33; Fig. 3C, left panel), and significantly better than the no-training group's performance pre-test (p<.0001; Cohen's d = 2.52) and post-test (p<.0001; Cohen's d = 2.38; Fig. 3C, right panel). Feeding performance in the no-training group did not change from pre-test to post-test (p=.99).

The number of beans spooned during the dual task condition was significantly lower than in the single task condition (main effect of condition: $F_{1,20}$=15.37; p<.001), as shown in Figure 3C. Dual task feeding performance was worse compared to single task feeding, regardless of group or session, as indicated by no significant interaction between condition (single task versus dual task) and group (training versus no-training) ($F_{1,20}$=1.58; p=.21). These results showed that for both groups, there was still significant dual task interference between the auditory and feeding tasks even in the post-test session. Thus, post-test feeding performance was still susceptible to dual task interference even in the training group. Only the training group, however, was able to spoon more beans while making fewer listening errors post-test compared to pre-test. This effect of training is highlighted in Figure 3D, which illustrates that across subjects, the no-training group showed no significant improvement in feeding task performance from pre- to post-test (one-sample t-test: single task p=.90; dual task p=.68).

Effects of transfer: Performance of simulated dressing under single and dual task conditions

Although the training group did not have any practice on simulated dressing, the single session of training influenced dressing performance. There was a significant interaction between session and group ($F_{1,20}$=7.42; p<.001). Post hoc analysis indicated that the training group's performance post-test was significantly better than pre-test (p<.0001; Cohen's d = 0.73; Fig. 4A, left panel), and better than the no-training group's performance pre-test (p=.0001; Cohen's d = 0.67) and post-test (p<.01; Cohen's d = 0.37; Fig. 4A, right panel). Dressing performance did not improve in the no-training group (p=.71). Improved performance in the training group, therefore, likely resulted from the transfer of training.

Dressing performance, unlike feeding performance shown in Fig. 3C, was similar in the single versus dual task conditions (main effect of condition: $F_{1,20}$=0.9; p=.34). There were no significant interactions between condition and session ($F_{1,20}$=1.21; p=.28) or between condition and group ($F_{1,20}$=1.98; p=.16). There was dual task interference initially when listening and dressing, however, as indicated by more listening errors in the pre-test session. Although dual task listening performance in the post-test session was comparable to listening only for both the training and no-training groups (see Fig. 2), results in Figure 4A indicate that only the training group was able to fasten more buttons while making fewer listening errors compared to pre-test. This effect is highlighted in Figure 4B, which illustrates that across subjects, the no-training group showed no significant improvement in dressing task performance from pre- to post-test (one-sample t-test: single task p=.28; dual task p=.22).

Effect of transfer: Specificity to motor performance

Improved motor performance due to training on the feeding task, however, did not transfer to the untrained nonmotor task (i.e. associative recognition). Similar to the training effects shown in Figure 3B, feeding performance at the end of training (trial 50) was significantly better than feeding performance at the start of training (trial 1; paired t-test p<.05). Despite showing significant improvement in feeding across the training session, these subjects showed no improvement in associative recognition from pre- to post-test (main effect of session: $F_{1,4}$=1.15; p=.31) or between single and dual task conditions (main effect of condition: $F_{1,4}$=0.4; p=.53). Overall, regardless of whether the associative recognition task was performed alone or concurrently with the auditory task, subjects performed similarly before (mean±SD: 54±16% correct) and after (59±22% correct) training. Thus, the effects of training transferred only to the

other motor task and not to the nonmotor task, given that the associative recognition task did not improve as a result of a single session of motor training. It is therefore unlikely that the training group's improvement on the untrained dressing task was due to increased levels of arousal and physical activity, but instead due to the transfer of training specifically within the motor domain.

DISCUSSION

The purpose of this study was to demonstrate the feasibility of using dual task paradigms to detect transfer of motor training. In doing so, the three criteria for this proof-of-principle were satisfied. First, dual task interference occurred in the pre-test condition when simultaneously performing each motor task with the auditory task. Although the number of listening errors in this study under dual task conditions (listening + motor) is small, it was significantly more than in the single task condition (listening only). Thus, the listening task used in this study appears to be sensitive enough to detect the presence of dual task interference, consistent with previous work in comparable sample sizes (Lang & Bastian, 2002). Second, both motor tasks were under-practiced and not over-learned with the nondominant hand, since one but not the other group showed improvement with training. Third, performance was measurable on both tasks and the units to measure performance were task-specific. By satisfying these three criteria within a single session of training, we were then able to test the feasibility of using dual task paradigms to detect transfer of motor training.

We found that for both the training and no-training groups, there was significant dual task interference between the auditory and motor tasks in the pre-test session, as evidenced by worse performance in the auditory task and/or in the motor tasks. By the post-test session, performance

of the auditory task improved, as evidenced by fewer listening errors in both groups under dual task conditions. The training group, however, was able to spoon more beans in the feeding task AND fasten more buttons in the dressing task while making fewer listening errors, whereas the no-training group showed no improvement in either motor task. Improved performance without practice on the dressing task, therefore, was likely due to transfer of motor training specifically rather than a general arousal effect that might be present after any training. This single session study introduces dual task paradigms as an alternative approach that may be applicable to a broader set of motor tasks while generating new questions about the effect of task selection, performance criteria, and training doses on the transfer process that can be addressed in future studies.

Mutual interference between auditory and motor tasks

In this study, the auditory task and the motor tasks appeared to mutually interfere with each other, given that both listening and motor performance were initially degraded in the dual task condition rather than one or the other. This mutual interference was found despite specific instructions to subjects to optimize listening performance. Listening performance on the auditory task was worse in the dual task conditions (listening + feeding; listening + dressing) compared to the single task condition in which only listening was required. These results suggest that despite the explicit instructions to the subjects to prioritize the auditory task, the motor tasks appeared to receive a higher priority with respect to allocation of attentional resources in the pre-test session. This may in part explain why pre-test dressing performance was similar under single and dual task conditions, at the cost of poorer listening performance. This is consistent with the idea that when attention is divided during lower extremity tasks, the nervous system often adopts a

“posture first” strategy for maintaining balance by allocating attentional resources to postural control and away from cognitive control (Doumas, Smolders, & Krampe, 2008; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). These studies have also demonstrated mutual interference between the primary and secondary tasks, thereby showing the attentional demands of postural control. Given that the motor tasks in the current study involved the upper rather than lower extremity, our results now provide further evidence that the control of naturalistic, functional movement relies on attentional resources that are susceptible to interference when doing another task simultaneously. Further work is needed, however, to more accurately determine the attentional cost of the upper extremity motor tasks.

Dual task interference can be viewed as a “central bottleneck” in processing that might suggest that, in this study, the neural resources necessary for planning and executing our selected motor tasks may overlap with those necessary for auditory vigilance (Pashler, 1994). By the post-test session, though, the motor tasks no longer interfered with listening performance in either the training or no-training group. While this might suggest that the effects of motor training were independent of the changes in the auditory task’s attentional load, it may also suggest that subjects quickly “learned” the auditory task. Thus, the amount of attention required for auditory vigilance was reduced in less than three listening trials, even though the target letters were changed each trial. If so, then more attentional resources would be available for executing each motor task. This rapid improvement in auditory vigilance is consistent with previous work, which demonstrated that after five trials, the same auditory task was resistant to dual task interference in a group of healthy adults as they performed a continuous motor task (Lang & Bastian, 2002). Further studies are necessary to test how specific motor and cognitive processes are related, and how changes in one domain might predict changes in the other. Nevertheless, the

presence of dual task interference in this study serves as rationale for pursuing how training and transfer may change the allocation of attention.

Measuring training and detecting transfer in naturalistic tasks

Our most important finding was that motor training on the simulated feeding task also improved the performance of the simulated dressing task in both the single and dual task conditions. In the post-test session, the training group fastened significantly more buttons while making fewer listening errors in the dual task condition compared to the pre-test session. In contrast, the no-training group showed no improvement in the dressing task, indicating that this improvement was directly due to motor training. The improved dressing task performance in one group and not the other strongly suggests that the effects of motor training had transferred. These results are important because measuring performance and detecting underlying processes are essential to any behavioral experiment (Stevens, 1951). Findings from this proof-of-principle study are therefore consistent with theoretical models and behavioral evidence of motor learning showing increased task automaticity due to training (Fitts & Posner, 1967; Giovannetti, et al., 2002; Kelly, et al., 2012; Lohse, 2011; Poldrack, et al., 2005; Wu, et al., 2004). Moreover, this study suggests that transfer of training may be detectable between naturalistic actions by using dual task paradigms.

What are some advantages and limitations of this novel approach?

There are three advantages of this approach to studying transfer of motor training. First, this approach may be used to study learning of purposeful, multi-step actions. Motor learning is a set of internal processes that cannot be measured directly, but is instead inferred based on behavior

(Schmidt & Lee, 1999; Shumway-Cook & Woollacott, 2007). Behavioral changes in components of naturalistic movement, like point-to-point reaching (Kluzik, Diedrichsen, Shadmehr, & Bastian, 2008; Krakauer, et al., 2000; Mattar & Ostry, 2010; Pearson, Krakauer, & Mazzoni, 2010; Pennel, Coello, & Orliaguet, 2002; Seidler, 2007; Shadmehr & Mussa-Ivaldi, 1994) or grasping (Albert, Santello, & Gordon, 2009; Bensmail, Sarfeld, Fink, & Nowak, 2010; Camus, Ragert, Vandermeeren, & Cohen, 2009; Liang et al., 2007; Parikh & Cole, 2011; Weigelt & Bock, 2010) underscore the nervous system's ability to transfer learning, but little work has investigated transfer between more complex, functional tasks. This proof-of-principle study offers the rationale of a new approach for probing changes in motor learning due to transfer that can be applied to a wider range of motor tasks than that which has been tested in previous studies of motor adaptation. Second, by considering how attentional demands change as a result of training, we were able to study transfer between two tasks that differed substantially in their movement patterns and goals. Similarity between motor tasks was not necessary for us to test the feasibility of this theory-based approach, although it is hypothesized that the amount of transfer between tasks depends on the degree of task similarity (Bills & McTeer, 1932; Deese, 1964; Gagne, et al., 1950; Holyoak & Koh, 1987; Poggio & Bizzi, 2004). A third and related advantage is that this approach is not limited to our selection of tasks. Although subjects in this study performed tasks involving auditory vigilance and simulated feeding and dressing, this approach may be feasible with a range of motor and cognitive tasks. For example, this approach could hypothetically be used to test whether training on an upper extremity task transfers to a lower extremity task, such as walking or sit-to-stand, in conjunction with a visual search task. Since this approach affords the ability to test different motor and cognitive tasks, it has potential to develop more ecologically valid methods to link real-world conditions with experimental

research (Brooks & Baumeister, 1977; Choi, Gordon, Park, & Schweighofer, 2011; Gioia, Kenworthy, & Isquith, 2010; Silver, 2000) that can address other critical aspects of the transfer process, such as whether the benefits of different types and durations of motor training extend beyond the motor domain to improve overall arousal levels or specific cognitive abilities.

Two important questions emerge from the results from this study. First, what transferred? Although this approach was able to detect behavioral evidence of transfer of training, it does not provide direct insight into the process or content of transfer. This has been a challenge for numerous psychophysical experiments designed to study transfer of motor training (for review see Adams, 1987) despite recent work in the neural mechanisms of transfer (Seidler, 2010). This current limitation can potentially be overcome with future studies that incorporate this paradigm in parallel with other established techniques such as repetitive transcranial magnetic stimulation (see Butefisch, Khurana, Kopylev, & Cohen, 2004; Khedr, Ahmed, Fathy, & Rothwell, 2005), structural and functional neuroimaging, pharmacological agents, computational models, or even exercise (see Swain, Harris, Wiener, Dutka, Morris, & Theien, 2003). In fact, many of these established methods have been used in single sessions of motor training in conjunction with other established behavioral assays such as kinematics and dynamics (for examples, see Krakauer, Mazzoni, Ghazizadeh, Ravindran, & Shadmehr, 2006; Shadmehr & Holcomb, 1997). Promising evidence from animal models suggests that repetitive training of complex skilled movements has been shown to produce significant, regionally-specific changes in neural structure and function within the brain (see Kleim & Jones, 2008) that may be candidate mechanisms of transfer. Future studies are needed, however, to probe the nervous system beyond the behavioral level to identify and test such mechanisms.

The persistent dual task interference during simulated feeding post-test suggests that the training session was not sufficient enough for subjects to become fully automatic, according to the phases of skill learning model (Fitts & Posner, 1967). This is not surprising, given that performance during the training session was not asymptotic (see Figure 3A), which could be attributed to the dose (50 trials) or condition (massed practice) of training. Thus, testing motor performance in dual task conditions could be a surrogate biomarker, like asymptotic adaptation, for how much learning (or transfer) has occurred (Sing & Smith, 2010). In light of these considerations, this proof-of-principle study raises a second question: What are the characteristics of transfer? This study was not designed specifically to test the nature of transfer, such as its time course or effects. It therefore does not address the persistent properties of motor learning and transfer (Schmidt & Lee, 1999). Rather, the goal of this single session study was to establish whether dual task paradigms could detect immediate transfer of motor training. This approach can now be expanded to test how transfer is influenced by the complexity and similarity of tasks or the amount, frequency, or duration of training, and could be used to study longer-term learning effects such as retention. In short, this single-session proof-of-principle study may provide opportunities for developing and testing future hypotheses related to motor performance, learning, and transfer.

Conclusions

Results from this study suggest that dual task paradigms may be a feasible approach to detecting transfer of training between naturalistic actions. By demonstrating improved performance of one motor task under dual task conditions as a result of practicing another motor task during a single session, our findings indicate that motor training can transfer, and suggest

that transfer can be measured using a dual task condition. Future work is needed to examine both the psychometrics of studying transfer with dual task paradigms and the longer-term effects of learning on movement automaticity.

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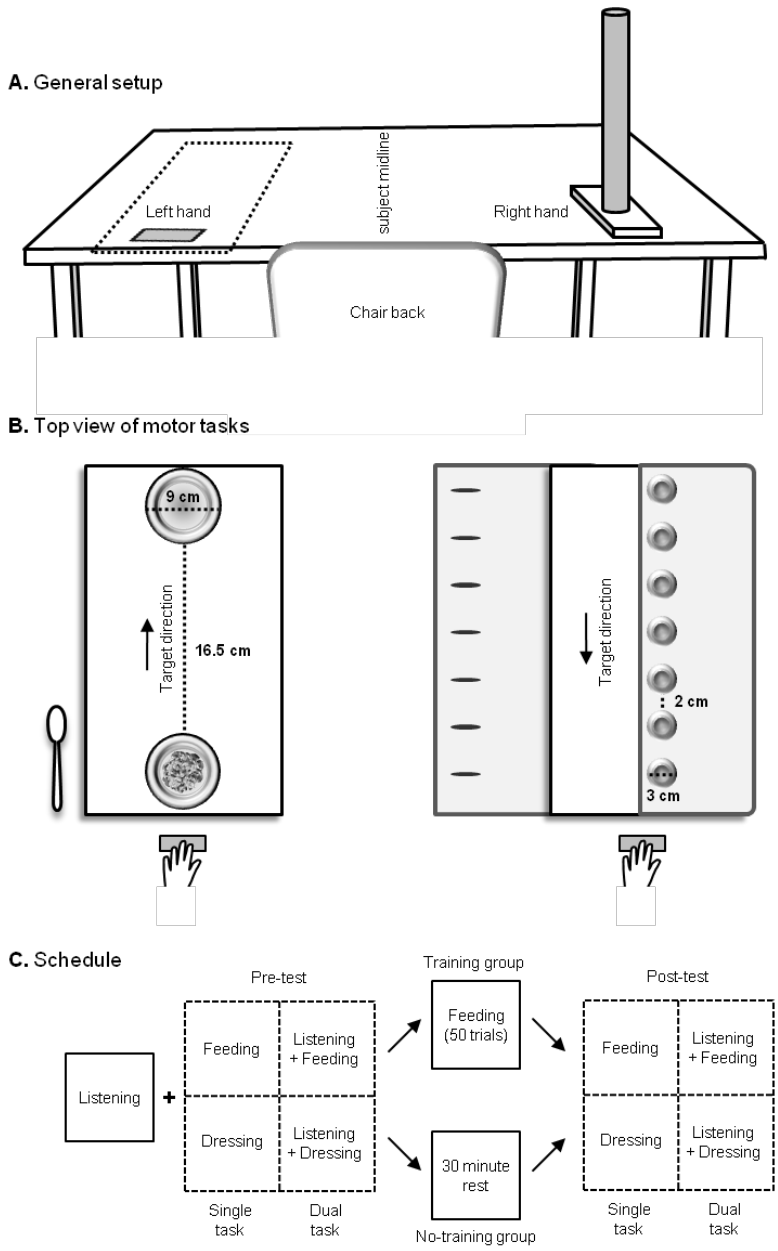

Figure 1. Materials and methods. (A) General setup for all tasks. Start locations for each hand are shaded gray: left hand on table, right hand on vertical cylinder. Dotted line indicates workspace for motor tasks. (B) Top view of motor tasks: trained task ("feeding", left panel) and untrained task ("dressing", right panel). (C) Diagram of task schedule. Dashed lines indicate pseudorandomized order of trials.

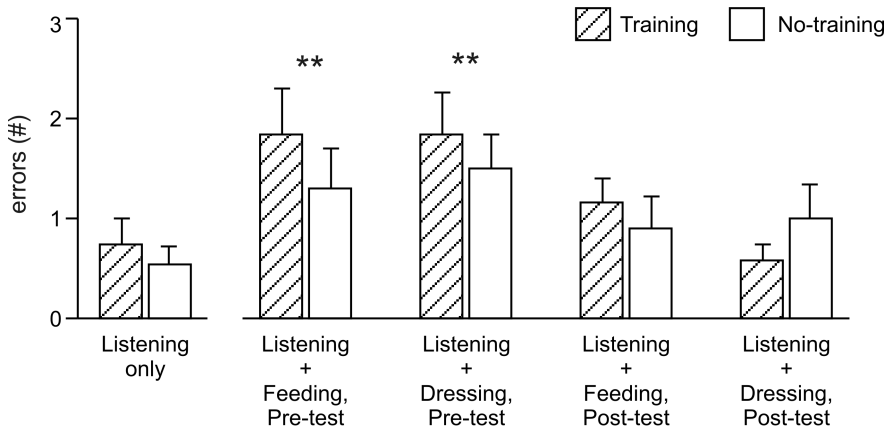

Figure 2. Dual task interference between auditory and motor tasks. Group mean ± SE number of errors in the listening only condition and dual task condition during pre- and post-test feeding and dressing for the training and no-training groups (Dunnett test, comparison to *Listening only* condition $^{**}p<.01$).

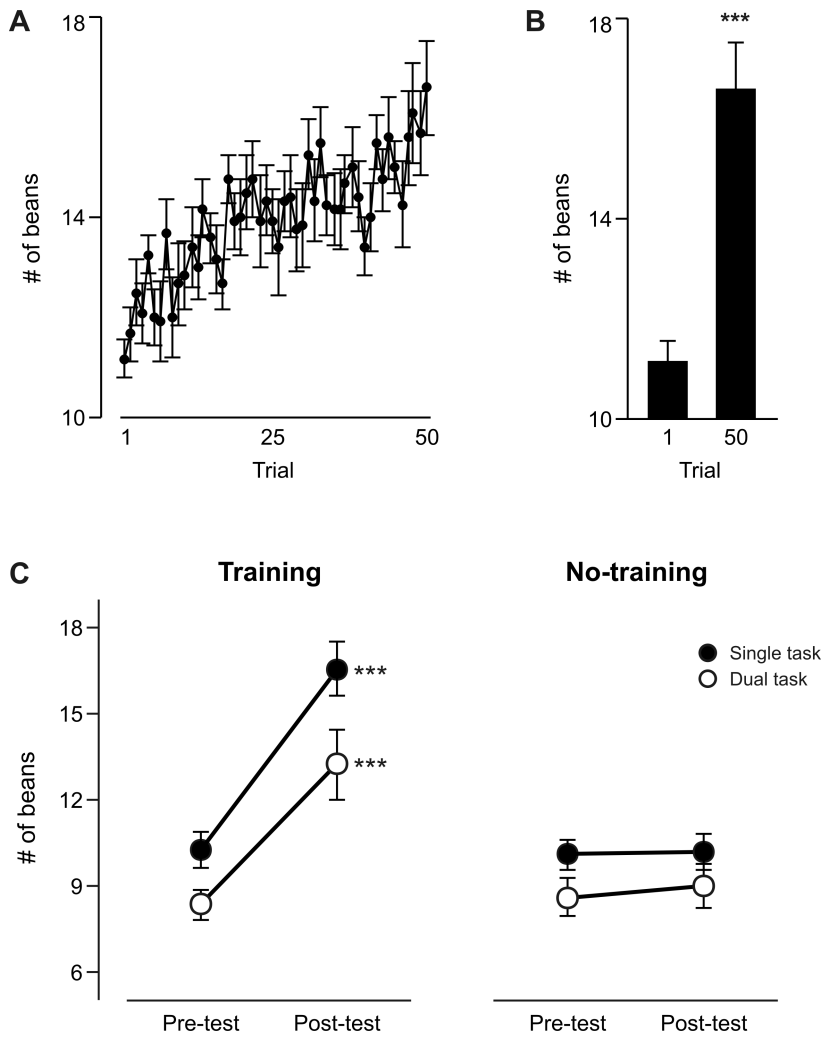

Figure 3. Effects of training: Performance of simulated feeding under single and dual task conditions. (A) Group mean ±SE number of beans spooned per 20-sec trial during training. (B) Group mean ±SE number of beans spooned in the first and last trial of training (*t*-test ***p<.0001). (C) Group mean ±SE number of beans spooned in the single task (filled circles) and dual task (open circles) conditions during pre-test and post-test performance for the training and no-training groups (Tukey HSD ***p<.0001). (D) Group mean ±SE improvement from pre- to post-test in the single and dual task conditions for the training and no-training groups. ANOVA results indicated only a significant main effect of group ($F_{1,20}$=35.94; p<.0001). Training group means were significantly different from zero (one-sample *t*-test ***p<.0001; **p<.01); no-training group means were not.

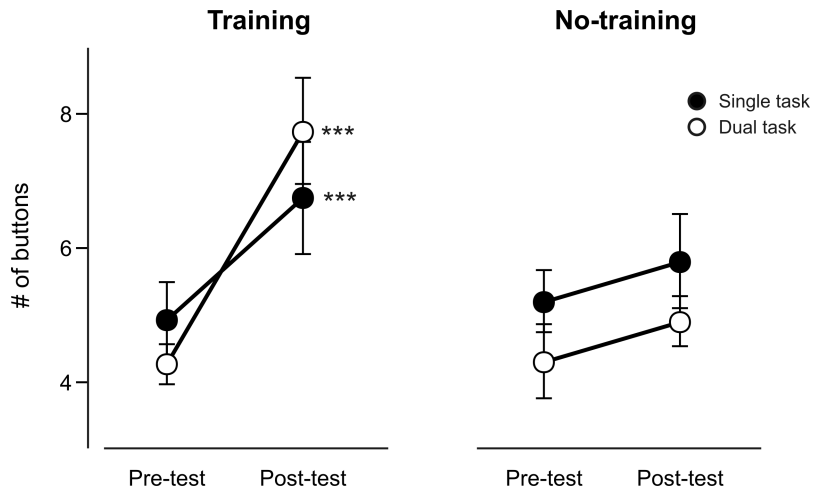

Figure 4. Effects of transfer: Performance of simulated dressing under single and dual task conditions. (A) Group mean ±SE number of buttons completed across subjects in the single task (filled circles) and dual task (open circles) conditions during pre-test and post-test performance for the training and no-training groups (Tukey HSD ***p<.0001). (B) Group mean ±SE improvement from pre- to post-test in the single and dual task conditions for the training and no-training groups. ANOVA results indicated only a significant main effect of group ($F_{1,20}$=5.62; p<.05). Training group means were significantly different from zero (one-sample t-test *p<.05; **p<.01); no-training group means were not.

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