THE CONTRIBUTION OF VERBALIZATION TO MOTOR PERFORMANCE

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A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Psychology

The University of Utah

December 2010

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

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ABSTRACT

Previous studies have shown that verbalization, in the form of self-guided instruction, is an effective cognitive strategy used to enhance motor skill acquisition and motor performance. However, past research has *not* explicitly examined which aspects of motor output are affected (whether beneficially or deleteriously) by verbalization. In the current study, we conducted two separate experiments in which a total of 80 healthy participants, ages 18-27, completed a novel motor sequence learning task. Half of the participants in each Experiment were pretrained in the sequence using verbalization, while the other half was either trained motorically, or not trained at all. Rote memorization of verbal labels facilitated motor learning, motor control, performance speed, and set maintenance, but not motor planning. Potential underlying mechanisms as well as clinical implications are discussed.

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INTRODUCTION

Over the last several decades much research has been dedicated to understanding the various factors that contribute to learning. While traditionally the majority of the literature has focused on either different types of learners within the classroom or different cognitive strategies used for acquiring academic or scholastic skills, recently, attention has turned to understanding the acquisition of complex motor skills. This latter line of research is broad, encompassing the acquisition of complex motor skills in athletes (Anderson, 1997; Landin, 1994), in individuals with movements disorders (i.e., developmental coordination disorder (DCD; Mandich, Polatajko, Missiuna & Miller, 2001)), and in brain-injured (i.e., stroke/traumatic brain injury (TBI)) individuals undergoing physical rehabilitation (O'Callaghan & Couvadelli, 1998). This research has begun to promote a “top-down” process of motor learning, one that encourages the use of cognitive strategies to enhance complex motor skill acquisition and transfer.

Cognitive strategies refer to conscious processes that learners can use as they internalize procedures in order to perform a specific task or skill (Anderson, 1997; McEwen, Huijbregts, Ryan & Polatajko, 2009). The literature addresses several different types of cognitive strategies that can be used to enhance the acquisition or the rehabilitation of motor skills, including mental practice, rehearsal, imagery, goal-setting, self-evaluation, and attention focusing. Such strategies have been shown to improve motor learning and overall motor performance, including accuracy and motor skill transfer (McEwen, et al., 2009; O'Callaghan & Couvadelli, 1998). The current paper focuses primarily on the use of verbalization (i.e., verbal self-instruction) as a cognitive strategy in motor skill learning (Anderson, 1997; McEwen, et al., 2009; O'Callaghan & Couvadelli, 1998).

The use of verbalization as a cognitive strategy emerged from the early work of Soviet psychologists Vygotsky (1987; 1978) and Luria (1959; 1961; 1964). Vygotsky, using a socio-cultural approach, was the first to theorize the importance, as well as the influence, of self-speech in the development and mediation of behavioral control, self-regulation, and other higher-order cognitive functions. Luria extended Vygotsky's work by emphasizing the role of self-speech in behavioral activation and impulse control (Harris, 1990). Through several studies utilizing experimenter-induced self-talk, Luria (1959; 1961; 1964) concluded that covert or overt vocalization that is paired with an action facilitates motor performance and motor skill acquisition, both in young children and in patients who have diminished capacity to internally control or regulate behavior.

Together these findings were fundamental to the later development of interventions utilizing verbalization (Harris, 1990). Among the first to develop such interventions were Meichenbaum and Goodman (1971), who utilized a cognitive-behavioral intervention that emphasized the use of experimenter-induced or experimenter-modeled verbalization to facilitate self-regulation in impulsive children. Since Meichenbaum and Goodman's original publication, the use of verbalization interventions has been adapted and used to facilitate the acquisition of complex motor skills in athletes (Anderson, 1997; Anderson & Vogel, 1999; Landin, 1994), young children (Vintere, Hemmes, Brown & Poulson, 2004), individuals with DCD (Mandich, et al., 2001), and individuals who have sustained a stroke or TBI (O'Callaghan & Couvadelli, 1998).

Research using verbalization interventions to facilitate motor skill acquisition has concluded that the use of verbalization results in faster motor skill acquisition (Anderson & Vogel, 1999; Vintere, et al., 2004), enhanced quality or execution of performance (Anderson & Vogel, 1999; Janelle, Champenoy, Coombes & Mousseau, 2003; Landin, 1994; Mandich, et al., 2001), and, in some cases, motor skill transfer from one task to another (Anderson, 1997; O'Callaghan & Couvadelli, 1998). These conclusions were drawn based on accuracy (i.e., number of errors) and form (i.e., body position) of participants' motor performances via direct observation (Anderson & Vogel, 1999; Janelle, et al., 2003; Vintere, et al., 2004).

While the majority of research supports the use of verbalization to facilitate motor skill acquisition, there are some inconsistencies within the literature that suggest that the use of verbal instructions may interfere with the implicit learning of a motor sequence in some populations. More specifically, Boyd, et al. (2003, 2004) found that individuals with focal lesions to the sensorimotor and basal ganglia regions did not benefit from explicit verbal information about the motor pattern embedded within an implicit motor sequencing task, while healthy controls did. In contrast, in a similar study with individuals with focal cerebellar lesions, Molinari, et al. (1997) found that explicit verbal knowledge of the embedded pattern did facilitate motor sequence learning.

The inconsistencies in the above findings may be a function of the fact that different populations exhibit deficits in different aspects of motor performance. In fact, past research has shown that discrete aspects of motor output are affected differently by different disorders. For example, research indicates that individuals with Parkinson's disease, Huntington's disease, or supplementary motor area infarcts have difficulties sequencing simple motor movements, despite being able to perform discrete individual movements correctly, albeit slowly (Benecke, Rothwell, Dick, Day, & Marsden, 1987; Dick, Benecke, Rothwell, Day & Marsden, 1986; Thompson, et al., 1988). These findings suggest that these individuals may have impairment in motor planning or motor learning, but *not* in motor control. In contrast, individuals with Alzheimer's disease exhibit normal ability to learn complex motor sequences, even though their performance speed is slow (Willingham, Peterson, Manning & Brashear, 1997). Further, there is evidence to suggest that there are subtypes of DCD that are characterized by different profiles of motor dysfunction. In particular, while some individuals with DCD exhibit impaired motor execution/control (i.e., coordination) in the context of intact motor planning, others show the opposite pattern (Cermak, 1985; Dewey, 2002; Dewey & Kaplan, 1994).

Taken together, these findings suggest that (1) verbalization or explicit verbal instruction are facilitative in some, but not all, situations or populations and (2) various disorders show impairments in different discrete aspects of motor output. However, past research has *not* explicitly examined which aspects of motor output are affected (whether beneficially or deleteriously) by verbalization. In other words, it may be that verbal instructions facilitate only some specific aspects of motor processing; consequently, only individuals with impairments in those particular discrete processes will benefit from the use of verbalization. Better understanding of which specific motor processes improve with the use of verbalization is important, as it would facilitate tailoring of rehabilitation or learning strategies towards specific populations that are the most likely to benefit.

In order to better understand how verbalization facilitates motor skill acquisition, we aimed to examine which discrete components of motor output are affected by verbalization. The components of motor output examined in this study included (1) *motor learning (M-LRN),* reflecting the number of errors made when learning the motor sequence, as well as the number of learning trials to criterion; and (2) *motor performance*, which consisted of (a) *motor planning (M-PLN),* reflecting the time it takes a person to plan and initiate a correct motor sequence, (b) *motor control (M-CNT),* reflecting the smoothness, speed, and accuracy of simple discrete movements, (c) *motor set-maintenance (M-SM)*, reflecting accuracy of movement sequences once the motor sequence has been learned, and (d) *performance speed (P-SPD),* reflecting the overall time to completion of a given sequence. Because this is the first study to examine the effects of verbalization on all of these discrete aspects of motor performance simultaneously, we chose to first examine this question in healthy college-aged individuals, prior to examining these processes in patient populations.

To accomplish these goals, we conducted two separate experiments using a computerized novel motor sequence learning task that allowed us to assess both motor learning (M-LRN) and individual components of motor performance (i.e., M-PLN, M-CNT, M-SM, and P-SPD). Experiment 1 compared motor learning and motor performance for two conditions: (a) learning motor sequence by *motor* imitation *with* concurrent *verbal* rote memorization of the sequence (i.e., *Verbalization+Action* condition) and (b) learning motor sequence by *motor* imitation *without* the use of any language (i.e., *Action Only* condition). Experiment 2 examined whether motor learning and performance would be facilitated by *previous* verbal rote memorization of the sequence (i.e., verbalization *without* motor practice).

EXPERIMENT 1

Method

Participants

A total of 40 healthy undergraduate students participated in this study. Participants were psuedorandomly assigned (controlling for gender) to one of two groups, for a total of 20 participants in the Verbalization+Action group and 20 participants in the Action Only group. Participants were recruited from the University of Utah's Department of Psychology's subject pool and each participant earned extra credit towards a psychology class in exchange for participation. Participants were right-handed, between the ages of 18 and 27, and spoke English as their first or primary language. To ensure that our sample was without any major impairment likely to affect our results, participants were screened using self-report measures for level of current depressive symptoms, the presence of ADHD symptoms, and executive abilities in everyday tasks. No significant differences were found between groups on any of the demographic variables. See Table 1 for detailed sample characteristics.

This study was approved by the University of Utah Institutional Review Board. Written consent was obtained from each participant prior to participation in the study.

Table 1.

Sample Demographics for Participants in Experiments 1 and 2

		Experiment 1		Experiment 2	
		V+A (*n* = 20)	**A (*n* = 20)**	**V (*n* = 20)**	**Control (*n* = 20)**
Age (yrs)	*M*	20.4	19.9	19.9	19.6
	SD	2.4	2.2	2.2	2.2
	Range	18-27	18-26	18-25	18-26
Education (yrs)	*M*	13.0	12.8	12.8	12.6
	SD	1.0	0.8	1.0	0.9
	Range	12-15	12-14	12-15	12-15
Gender (% Male)		50%	45%	55%	40%
Estimated FSIQ	*M*	105.2	102.9	106.9	105.9
	SD	6.5	8.5	6.0	5.4
	Range	90-117	81-117	95-116	97-116
BDI-II	*M*	4.8	7.0	5.8	6.7
(Total Score)	*SD*	4.1	6.4	6.5	4.0
	Range	0-13	0-24[1]	0-28[1]	0-16
BRIEF: GEC	*M*	47.0	49.6	46.6	46.0
(*T*-score)	*SD*	6.2	7.2	6.4	6.1
	Range	38-61	37-60	37-61	36-59
CAARS: ADHD	*M*	47.9	50.7	47.6	45.8
Symptom Total	*SD*	7.6	11.5	11.9	8.9

Table 1. *Continued*

(*T*-score)	Range	40-64	33-75	32-82	32-63

Note. V+A = Verbalization+Action group; A = Action Only group; V = Verbalization Only group; Control = Control group; FSIQ = Full Scale IQ; BDI-II = Beck Depression Inventory-II; BRIEF = Behavioral Rating Inventory of Executive Functions; GEC = Global Executive Composite; CAARS = Conners Adult ADHD Rating Scale
No significant differences were found between groups across any of the demographic variables.

Instruments and Materials

Motor learning task

The motor learning task used in this study was based on the Push-Turn-Tap-tap (PTT) task from the Behavioral Dyscontrol Scale-Electronic Version (Suchy, Derbidge & Cope, 2005). Participants performed a sequence of five hand movements using the BDS-EV response console (Figure 1). The sequence was comprised of three different movements: (1) Push, pushing the joystick/lever upward one time, (2) Turn, turning the joystick/lever to the right one time, and (3) Tap-tap, tapping a large button two times. The sequence was psuedorandomized to control for more than two movements being repeated in a row. The sequence was the same for all participants across both experiments.

Participants in the Verbalization+Action group were trained in a rote fashion by performing the sequence on the BDS-EV response console while observing a model and simultaneously vocalizing the verbal labels for each movement (i.e., using verbalization) as they performed the action. Participants in the Action Only group were also trained by

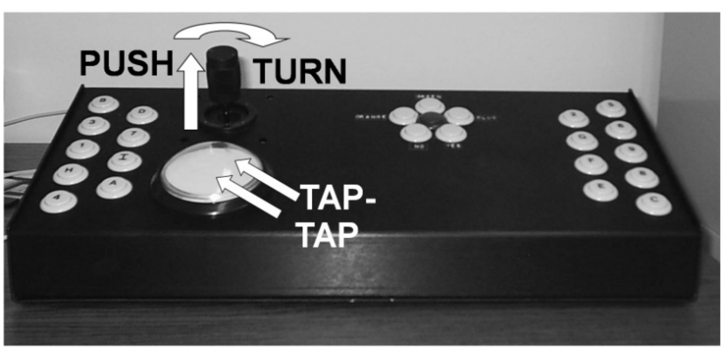

Figure 1. *Behavioral Dyscontrol Scale – Electronic Version Response Console (Suchy, Derbidge, & Cope, 2005).* Participants were asked to perform a sequence of five hand movements (e.g., "turn," "push," "turn," "taptap," "push") using the BDS-EV Response Console.

performing the sequence on the BDS-EV response console while observing a model; however, in order to suppress verbal encoding, participants were required to vocalize “ba ba ba ba” while performing the sequence, similar to procedures used previously by Baddeley and colleagues (2001). It is important to note that for the Action Only group, the words “push, turn, tap-tap” were never used to describe the movements being completed.

Learning trials. Participants in both groups were trained to a predetermined criterion during the Learning Trials using a series of videos in which a model performed the sequence of movements with and without verbalization. The purpose of the Learning Trials was to ensure that each participant learned the sequence well enough so that it was no longer kept within working or short-term memory. The criterion was defined as the ability to perform the correct movement sequence five consecutive times without error following two separate brief distraction periods (see Figure 2 for a flow chart of motor learning to criterion). During each distraction period, participants spent approximately 3 minutes engaging in performance of paper and pencil tasks that consisted of visual scanning, sequencing of numbers or letters, or connecting dots in a certain order as quickly as possible.

The total number of training trials it took for each participant to reach criterion was recorded by hand.

Performance trials. After being trained to the predetermined learning criterion, all participants completed the Performance Trials. The purpose of the Performance Trials was to examine the effect of previous training across the four components of motor

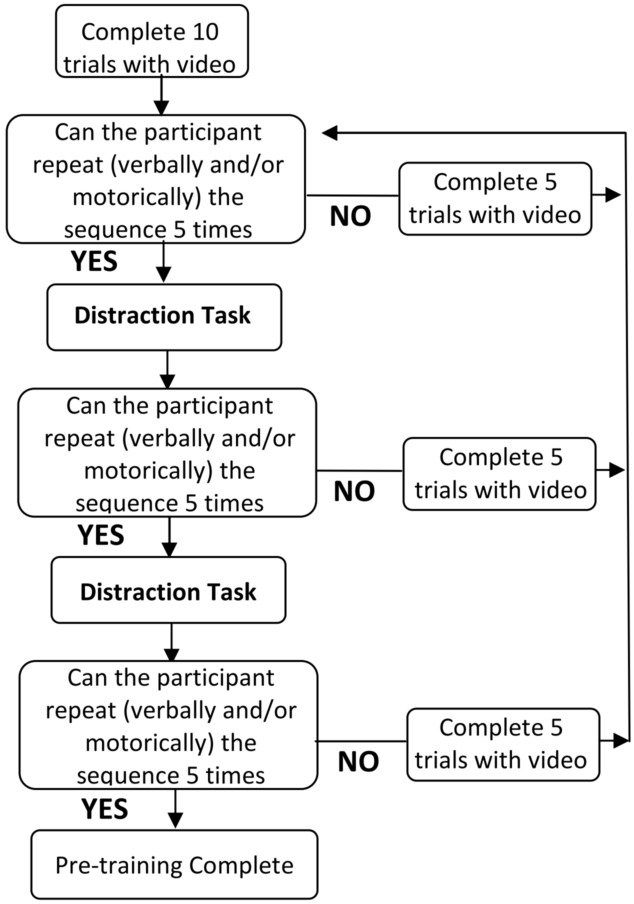

Figure 2. *Training to Criterion Flow Chart.* Participants in the Verbalization+Action, Action Only, and Veberalization Only groups were pretrained in the sequence either verbally and/or motorically depending on group assignment. In order to proceed from the training session to performance trials, participants had to perform the correct movement sequence, in the method in which they were trained, five consecutive times without errors following two separate brief distraction periods. In the case of the Verbalization Only group, participants did not perform the movement sequence, but rather recited the sequence verbally (i.e., "push, turn, taptap, etc."). During each distraction period, participants spent approximately 3 minutes engaging in performance of paper and pencil tasks that consisted of visual scanning, sequencing of numbers or letters, or connecting dots in a certain order as quickly as possible. For the participants in the Verbalization+Action and Action Only groups (i.e., participants in Experiment 1) training to criterion constituted the Learning Trials. Once training was complete, participants proceeded to the Performance Trials. In contrast, once the participants in the Verbalization Only group (i.e., participants in Experiment 2) reached the learning criterion they proceeded to the practice trials along with the Control group.

performance. More specifically, the Performance Trials examined whether or not pairing verbalization with action facilitated motor performance above and beyond just learning the sequence motorically. The Performance Trials consisted of nine repetitions of the five-movement motor sequence. The four components of motor performance (described below; M-PLN, M-CNT, M-SM, and P-SPD) were recorded on the computer. Errors were followed by an audible beep and an "error" screen depicting the correct movement; participants were to perform the correct movement and to continue on with the sequence like before.

Motor learning task variables. The motor learning task yielded five variables: (1) M-LRN, (2) M-PLN, (3) M-CNT, (4) M-SM, and (5) P-SPD. All variables except for M-LRN were recorded via computer during the Performance Trials.

Motor learning (M-LRN). M-LRN reflects the number of trials each participant took to learn the movement sequence and to reach the criterion during the Learning Trials.

Motor planning (*M-PLN).* M-PLN refers to the internal model or action plan that precedes the correct motor commands in order to achieve the final movement goal (Buxbaum, 2005), taking into account both the movement goal and the discrete muscular movements that will be required (Keele, 1968). Following the methodology of Suchy and Kraybill (2007), M-PLN was assessed by measuring the amount of time it took each participant to plan the complete movement sequence. Thus, M-PLN time was considered to be the latency time between the last movement of the preceding sequence and the first movement of the next correct sequence. Latencies that preceded incorrect sequences were not included because this variable was designed to measure the time to plan correct sequences.

Motor control (M-CNT). M-CNT refers to the planning and correct execution of discrete movements (Whiting, Vogt & Vereijken, 1992; D. B. Willingham, 1998) and is considered a separate and unique construct from both M-SM and M-PLN (Suchy & Kraybill, 2007; Whiting, et al., 1992). Following the methodology of Suchy and Kraybill (2007), the speed, accuracy, and smoothness of the double tap, or tap-tap movement, was used to examine M-CNT. If the movement was performed accurately (e.g., there were no perseverative responses), the latency time between the first tap and the second tap was recorded for each trial/sequence.

Motor set-maintenance (M-SM). M-SM refers to performance accuracy across trials once the motor sequence has been learned. M-SM was assessed by counting the total number errors made across each performance trial/sequence. It should be noted that errors made on the tap-tap movement (e.g., conducting a single tap instead of double tap) were excluded from this total given that those errors are considered to reflect M-CNT rather than M-SM.

Performance speed (P-SPD). P-SPD is directly impacted by how well the sequence has been learned and refers to the total amount of time required for completion of the entire sequence, measured in ms. P-SPD was calculated for all movement sequences regardless of errors made.

Cognitive and Psychiatric Screening

All participants underwent a brief cognitive exam and completed three behavioral/psychiatric inventories. The Shipley Institute of Living Scale (Zachary, 1986) was used to derive an estimate of Full Scale IQ (FSIQ). Since depressive symptomology is known to correlate with motor performance, we used the Beck Depression Inventory-II (BDI-II: Beck, Steer & Brown, 1996) to screen for the presence of moderate to severe depression. Similarly, it is likely that both executive ability and attention also correlate both with motor performance and learning; therefore, we used the Behavioral Rating Inventory of Executive Functioning-Adult Version (BRIEF-A: Roth, Isquith & Gioia, 2000) to screen for executive impairment and the Conners Attention Deficit Disorder Scale- Self-Report: Long Version (CAARS-S:L: Conners, Erhardt & Sparrow, 1998) to screen for attention problems. Standard administration procedures were followed for all screening instruments.

Procedures

Participants were psuedorandomly assigned (controlling for gender) to one of the two learning groups. Participants first completed the Learning Trials. Once the pre-determined learning criterion was reached, participants proceeded to the Performance Trials. There was a short break between the Learning and Performance Trials that lasted approximately 1-2 minutes, just long enough for the Performance Trials' program to be started and the instructions given. Following the motor sequence learning task, participants completed the brief cognitive assessment and filled out three behavioral/psychiatric inventories. The total testing session lasted approximately 1 hour.

Results

Preliminary Analyses

Zero-order correlations among the dependant variables are shown in Table 2. As expected, M-PLN and M-CNT times are positively correlated with P-SPD. Additionally, analyses indicated a significant correlation between M-LRN and M-CNT, in that the more trials it takes to reach criterion the slower the tap-tap movement is executed. Partial correlations were also conducted controlling for Group membership; however, no differences were found in the outcome of the results and thus the relationship between the variables is not an artifact of Group. See Table 3.

Principal Analyses

Learning trials. Nonparametric tests of the number of learning trials to reach criterion found that the Verbalization+Action group took significantly fewer trials to

Table 2.

Zero Order Correlations Among Dependent Variables in Experiment 1

	M-PLN Time	M-CNT Time	M-SM Errors	P-SPD Time
M-LRN Total Trials	.026	.429**	.097	.286
M-PLN Time		.190	-.198	.638 **
M-CNT Time			-.030	.652**
M-SM Errors				-.136

Note. M-LRN = Motor Learning; M-PLN = Motor Planning; M-CNT = Motor Control; M-SM = Motor Set Maintenance; P-SPD = Performance Speed
** indicates a correlation that is significant at the .01 (two-tailed) level.

Table 3.

Partial Correlations Among Dependent Variables Controlling for Group in Experiment 1

	M-PLN Time	M-CNT Time	M-SM Errors	P-SPD Time
M-LRN Total Trials	.030	.321*	.031	.194
M-PLN Time		.180	-.228	.655 **
M-CNT Time			-.065	.598**
M-SM Errors				-.225

Note. M-LRN = Motor Learning; M-PLN = Motor Planning; M-CNT = Motor Control; M-SM = Motor Set Maintenance; P-SPD = Performance Speed
* indicates a correlation that is significant at the .05 (two-tailed) level.
** indicates a correlation that is significant at the .01 (two-tailed) level.

reach criterion than the Action Only group (Mann–Whitney $U = 128.5$, $n_1 = 20$ $n_2 = 20$, $p = .008$ two-tailed). These findings suggest that the pairing of verbalization with action facilitated initial M-LRN of the complex motor sequence above and beyond just learning the sequence motorically.

Performance trials. A total of nine sequence trials were completed during the Performance Trials. For the purpose of the statistical analyses, these nine trials were grouped into three Blocks, with each Block reflecting a mean performance value of three contiguous sequence trials. These mean values were used as dependent variables, and Block (i.e., 1st, 2nd, and 3rd) was used as the within-subjects factor. For all analyses, Group was used as the between-subjects factor. Statistics of interest included (a) a main effect of Group which would indicate an effect of the type of prior training on performance (as measured by the motor variables), and (b) a significant interaction between Block and Group, which would reflect that prior training has a differential effect on performance across the three Blocks of trials.

Motor Planning (M-PLN). Two-group repeated measures ANOVA of M-PLN time across Performance Blocks revealed no significant Group X Block interaction [$F(2, 76) = .278$; $p = .758$, $\eta_p^2=.005$] and no significant differences in performance between the two Groups [$F(1, 38) = .044$; $p = .835$, $\eta_p^2=.001$]. These findings suggest that verbalization did not facilitate M-PLN above and beyond just learning the sequence motorically. However, there was a significant effect of Block [$F(2, 76) = 22.65$; $p < .001$, $\eta_p^2=.373$], with both groups exhibiting significantly longer M-PLN time during Block 1 as compared to Blocks 2 and 3. It is likely that the longer M-PLN time during the initial performance Block is associated with the brief interruption in performance when transitioning from the Learning to the Performance Trials. See Figure 3a.

Motor Control (M-CNT). Two-group repeated measures ANOVA of M-CNT time across the Performance Blocks indicated a significant effect of Group [$F(1, 38) = 5.77$; $p = .021$, $\eta_p^2=.132$], with the Verbalization+Action group exhibiting significantly faster M-CNT time than the Action Only group across all performance Blocks. In contrast, a one-way ANOVA revealed that there were no Group differences in M-CNT accuracy [$F(1, 38) = .147$; $p = .703$; Cohen's $d = .12$]. This suggests that verbalization paired with action serves as a useful tool to facilitate smooth and rapid execution of discreet movements, but not necessarily the accuracy of the movements. There was no significant effect of Block [$F(2, 76) = .082$; $p = .921$, $\eta_p^2=.019$] or Group X Block interaction [$F(2, 76) = .149$; $p = .862$, $\eta_p^2=.002$]. See Figure 3b.

Motor Set Maintenance (M-SM). Two-group repeated measures ANOVA of M-SM across the Performance Blocks yielded a significant Group X Block interaction [$F(2, 76) = 4.90$; $p = .033$, $\eta_p^2=.114$], indicating that accuracy was affected differently across the Blocks depending on Group. Follow-up analyses indicated that the interaction was primarily accounted for by differences in mean M-SM performance on Block 1, with the Action Only group exhibiting significantly more errors than the Verbalization+Action group [$t(1, 38) = -2.30$; $p = .027$; Cohen's $d = .73$]. Similar to M-PLN, this pattern of performance suggests that the participants in the Action Only group likely experienced a loss of set associated with the brief interruption between the Learning and Performance trials. Overall, these findings suggest that verbalization paired with action facilitates M-SM across a shift in environment. No significant main effects of Block [$F(2, 76) = .029$; $p = .866$, $\eta_p^2=.001$] or Group [$F(1, 38) = .912$; $p = .346$, $\eta_p^2=.023$] were found. See Figure 3c.

Performance Speed (P-SPD). Two-group repeated measures ANOVA of P-SPD time across Performance Blocks revealed no significant Group X Block interaction [$F(2, 76) = .165$; $p = .687$, $\eta_p^2=.004$] and no significant differences in performance between Groups [$F(1, 38) = 2.63$; $p = .113$, $\eta_p^2=.065$]. As with M-PLN, these findings suggest that verbalization did not facilitate P-SPD above and beyond just learning the sequence motorically. However, there was a significant effect of Block [$F(2, 76) = 14.38$; $p = .001$, $\eta_p^2=.274$], with both groups exhibiting significantly slower P-SPD time during Block 1 compared to Blocks 2 and 3 (See Figure 3d). This is consistent with the longer planning time exhibited by both Groups during Block 1.

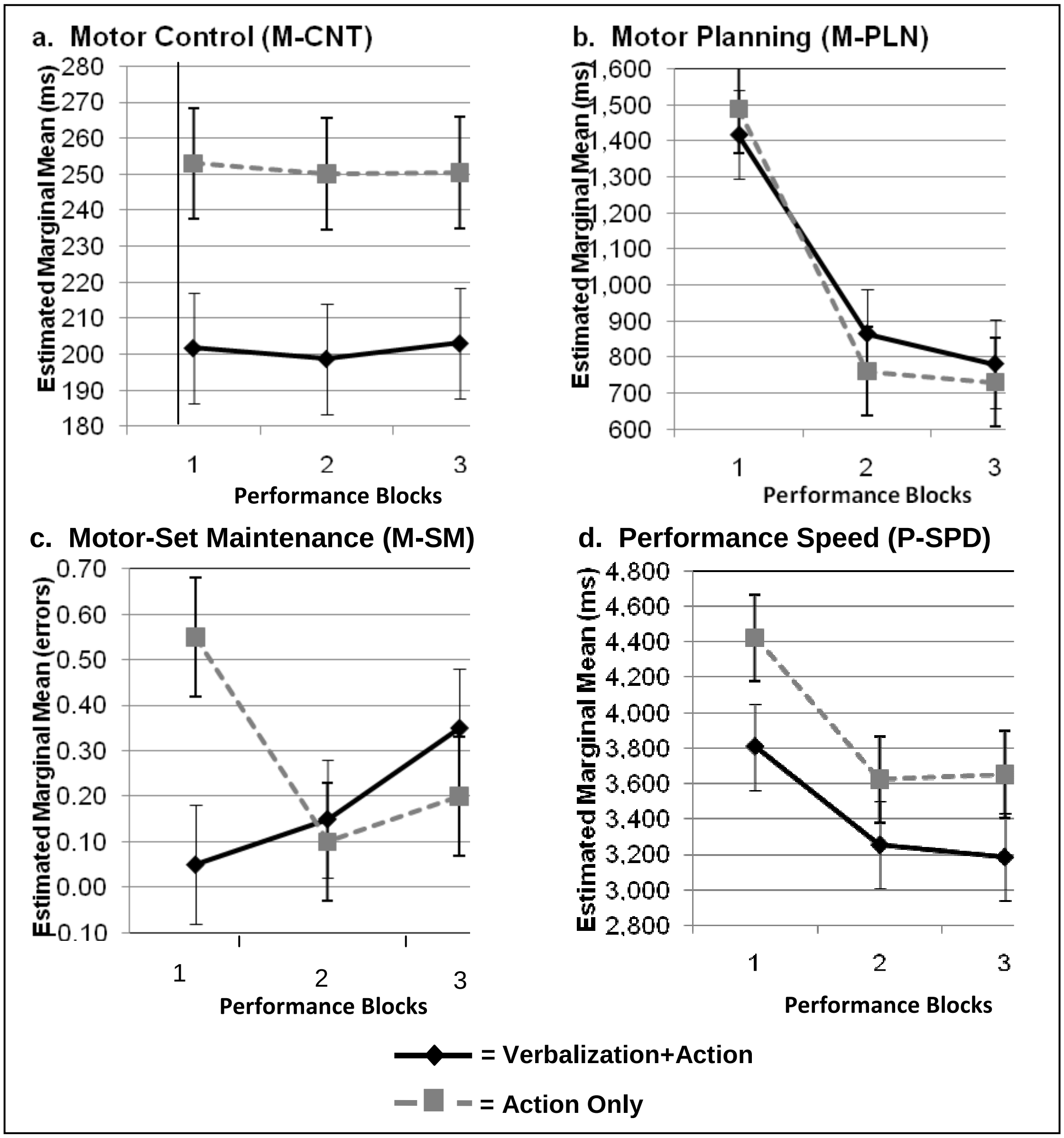

Figure 3. *Experiment 1: Performance on the Discrete Motor Components Across Performance Blocks.* Participants in the Verbalization+Action group were pre-trained in the motor sequence by simultaneously performing the action sequence and by verbalizing the labels of each movement (i.e., "push, turn, taptap"). Participants in the Action Only group were pretrained in the motor sequence by performing the action sequence, and in order to suppress verbal encoding of the sequence, they simultaneously performed a verbal interference task (i.e., saying "ba, ba, ba" out loud). All participants completed Learning Trials, during which they were trained in the sequence to a predetermined learning criterion. Following the Learning Trials all participants completed the Performance Trials, which consisted of a total of nine sequence trials. For the purpose of the statistical analyses, these nine trials were grouped into three Blocks, with each Block reflecting a mean performance value of three contiguous sequence trials. **a.** Line graph

showing mean M-PLN latencies (in ms) across Performance Blocks. While there was no significant interaction or main effect of Group, a significant main effect of Block was revealed (p = .001), with both Groups showing significantly longer M-PLN on Block 1 compared to the later Blocks. **b.** Line graph showing mean M-CNT latencies (in ms) across Performance Blocks. Analyses yielded a significant main effect of Group (p = .021). **c.** Line graph showing mean M-SM errors across Performance Blocks. Analyses revealed a significant Group X Block interaction (p = .033). Follow-up analyses indicated that the interaction was driven by a significant group difference on Performance Block 1 (p = .027). **d.** Line graph showing mean P-SPD time (in ms) across Performance Blocks. While there was no significant interaction or main effect of Group, a significant main effect of Block was revealed (p = .001), with both Groups showing significantly slower P-SPD on Block 1 compared to the later Blocks.

Figure 3. *Continued*

Discussion

The findings from Experiment1 suggest that verbalization facilitates some aspects of motor performance, but not all. Participants who learned the motor sequence by pairing verbalization with action took significantly fewer trials to learn the motor sequence than the group who only learned the sequence motorically. Similarly, once the sequence has been learned, the group that learned the motor sequence using verbalization paired with action exhibited better performance on some, but not all, aspects of motor output. In particular, the use of verbalization facilitated M-CNT speed and better maintenance of performance accuracy across the Performance Trials, particularly when following a brief interruption between Learning and Performance Trials. Pairing verbalization with action did not appear to facilitate the planning of action sequences or performance speed above and beyond just learning the sequence motorically. However, both M-PLN and P-SPD seemed to be affected by the brief interruption between the Learning and Performance Trials. More specifically, both groups showed increased mean times on Block 1 compared to Blocks 2 and 3 indicating an improvement in performance across the Blocks.

EXPERIMENT 2

While Experiment 1 shed some light on the contribution of verbalization to discrete components of motor learning, it remained unclear as to whether or not it was the pairing of the action and verbalization, or whether or not verbalization *alone* would be sufficient to facilitate certain aspects of motor performance. Experiment 2 allowed us to tease these different mechanisms apart. In Experiment 2, we examined if over-learning the verbal labels of the sequence in a rote fashion *prior to* actually performing the sequence motorically was enough to facilitate motor learning and motor performance.

Method

Participants

A separate group of 40 healthy undergraduate students participated in this study. Participants in Experiment 2 were pseudorandomly assigned (controlling for gender) to one of two groups. 20 participants were assigned to the *Verbalization Only* group and 20 participants were assigned to the *Control* group. Again, participants were recruited from the University of Utah's Department of Psychology's subject pool and each participant earned extra credit towards a psychology class in exchange for participation. Participants met the same eligibility criteria as described in Experiment 1. No significant differences were found between groups on any of the demographic variables. See Table 1 for detailed sample characteristics. This study was approved by the University of Utah Institutional Review Board. Written consent was obtained from each participant prior to participation in the study.

Instruments and Materials

Motor learning task. Using the same criterion described in Learning Trials of Experiment 1 (see Figure 2), participants in the Verbalization Only group rote-memorized the verbal labels of the motor sequence. More specifically, participants were trained to vocalize the action labels "push," "turn," and "tap-tap," without having the benefit of seeing a model perform the sequence or the BDS-EV response console. Additionally, in order to suppress gestural or motoric encoding of the task sequence, participants were required to simultaneously pat their hands on the table. After reaching the criterion, participants in the Verbalization Only group proceeded to the practice trials (described below). Participants in the Control group proceeded to practice trials without any pretraining of the motor sequence or the verbal labels. It should be noted that the Control group paired action and verbalization from the beginning; however, they did not have the opportunity to over-learn the sequence as the other groups did.

Practice. Both the Verbalization Only and the Control group completed three practice trials. The purpose of the practice trials was to introduce the task, providing brief exposure to the correct execution of each movement and the correspondence between movements and labels. This was necessary because neither group had any previous knowledge of how to execute the sequence. Following brief instructions on how to use the BDS-EV response console, the verbal labels of the five-movement sequence were displayed on the computer screen, with the movement that was to be performed displayed in capital letters. If the movement was performed incorrectly, participants received an audible beep and an "error" screen that remained until the movement was executed correctly. The movements of the sequence were presented in this manner until the participants complete three trials of the five-movement sequence.

Learning and performance trials. At the end of the practice trials, participants immediately proceeded to the Learning and Performance Trials, at which point the verbal labels on the screen disappeared and the participants continued to perform the sequence of movements from memory for an additional 15 trials. As with Experiment 1, each trial consisted of the five-movement motor sequence. Participants were told in advance that the instructions would disappear, at which point they were to continue to perform the sequence from memory. As with the practice trials, errors were followed by an audible beep and an "error" screen that remained until the correct movement was executed. Otherwise, the computer screen remained black.

As with Experiment 1, after the groups learned the motor sequence, performance was assessed. For the purpose of Experiment 2, the sequence was considered "learned" when (1) there no longer was a learning curve (i.e., there were no differences in accuracy) from one trial to the next, and (2) the groups exhibited comparable accuracy to (a) each other and (b) both Groups from Experiment 1 (i.e., there were no longer any differences in the number of errors among the four groups).

Motor learning task variables. As was the case with Experiment 1, the motor learning task yielded five variables: (1) M-LRN, (2) M-PLN, (3) M-CNT, (4) M-SM, and (5) P-SPD. M-PLN, M-CNT, M-SM, and P-SPD were measured following the methodology described in Experiment 1. All variables were recorded on the computer. M-LRN is described below.

Motor learning (M-LRN). M-LRN refers to an increase in movement accuracy with practice over time (Willingham, 1998). Therefore, we used accuracy to establish that adequate learning has taken place. This construct was assessed by counting the total number errors made. It should be noted that errors made on the second tap of the tap-tap movement were excluded from this total given that those errors are associated with motor control rather than motor learning.

Cognitive and Psychiatric Screening

All participants underwent the same brief cognitive exam and completed the same three behavioral/psychiatric inventories as described in Experiment 1.

Procedures

Participants were pseudorandomly assigned (controlling for gender) to one of two Groups: (1) Verbalization Only group or (2) Control group. Participants in the Verbalization Only group underwent pretraining to criterion as described in the Learning Trials of Experiment 1. Next, both groups completed three practice trials, which were immediately followed, without interruption, by the Learning and Performance Trials. Following the motor sequence learning task, participants completed the brief cognitive assessment and filled out three behavioral/psychiatric inventories. The total testing session lasted approximately 1 hour.

Results

The Learning and Performance Trials of Experiment 2 consisted of 15 sequence trials. Similar to Experiment 1, for the purpose of the statistical analyses, the 15 trials in Experiment 2 were grouped into five Blocks with each Block consisting of three trials. For M-LRN, the total number of errors was calculated across the three sequence trials within each Block. For the four motor performance variables, mean performance was calculated across the three sequence trials within each Block. This allowed for a total of five Blocks, which served as the within-subjects factors. Learning and performance values were use as the dependant variables. For all analyses Group was used as the between-subjects factor. Statistics of interest were the same as those described in Experiment 1.

Preliminary Analyses

Zero-order correlations among the dependant variables are shown in Table 4. As expected, all variables are positively correlated with M-LRN. This suggests that how well one learns the motor sequence contributes to all discrete components of motor performance. Also as expected, M-SM, M-PLN, and M-CNT positively correlate with P-SPD. Lastly, the analyses revealed that M-PLN is positively correlated with M-SM. This correlation suggests that participants may be taking longer to plan the action sequence following an error in the preceding trial. As with Experiment 1, partial correlations were also conducted, controlling for group membership. There were no differences in the outcome of the results, with the exception of a slight loss in significance on the M-SM and M-PLN correlation, demonstrating that the relationship among the variables is not an artifact of Group. See Table 5.

Principal Analyses

Learning trials. In order to fully examine the contribution of verbalization training to the discrete motor components, we first separated the learning trials from the performance trials. As described above, the sequence was considered learned when (1)

Table 4.

Zero Order Correlations Among Dependent Variables in Experiment 2

	M-PLN Time	M-CNT Time	M-SM Errors	P-SPD Time
M-LRN Errors	.407**	.467**	.602**	.698*
M-PLN Time		.153	.355*	.615 **
M-CNT Time			-.012	.505**
M-SM Errors				.518**

Note. M-LRN = Motor Learning; M-PLN = Motor Planning; M-CNT = Motor Control; M-SM = Motor Set Maintenance; P-SPD = Performance Speed
* indicates a correlation that is significant at the .05 (two-tailed) level.
** indicates a correlation that is significant at the .01 (two-tailed) level.

there no longer was a learning curve (i.e., there were no differences in accuracy) from one trial to the next, and (2) the groups exhibited comparable accuracy to (a) each other and (b) the mean performance of both groups from Experiment 1 (i.e., there were no longer any differences in the number of errors among the four groups).

First, to determine at which point there no longer was a learning curve, we conducted a within-subjects repeated measures ANOVA using accuracy as the dependant variables and block as the within subjects factor. A separate analysis was used for each group. The results indicated that both the Verbalization Only and the Control groups exhibited a learning curve across Blocks [$F(1, 19) = 4.618$; $p = .045$, $\eta_p^2=.196$] and [$F(1, 19) = 9.264$; $p = .007$, $\eta_p^2=.328$], respectively. Although both groups showed learning across Blocks, the Control group exhibited a steeper learning curve than did the Verbalization Only group, indicating that the groups learned the motor sequence at

Table 5.

Partial Correlations Among Dependent Variables Controlling for Group in Experiment 2

	M-PLN Time	M-CNT Time	M-SM Errors	P-SPD Time
M-LRN Total Trials	.334*	.396*	.572**	.654**
M-PLN Time		.077	.311	.578**
M-CNT Time			-.086	.452**
M-SM Errors				.482**

Note. M-LRN = Motor Learning; M-PLN = Motor Planning; M-CNT = Motor Control; M-SM = Motor Set Maintenance; P-SPD = Performance Speed
* indicates a correlation that is significant at the .05 (two-tailed) level.
** indicates a correlation that is significant at the .01 (two-tailed) level.

different rates across the Blocks of trials. Paired-comparison *t*-tests revealed that although there were differences between blocks 1 and 2, there were no longer differences in M-LRN between Blocks 2 and 3 for either Group, with p >.10 and Cohen's d = .61. These findings indicate that there was no learning curve beyond Block 2 for either Group.

Next, to determine when performance accuracy was comparable between Groups we completed t-tests comparing the two Groups on M-LRN across the Blocks. These analyses indicated that the Verbalization Only group made significantly fewer errors than the Control group on Blocks 1 and 2, [t(1, 38) = -2.67; p = .011; Cohen's d = .84] and [t(1, 38) = -2.75; p = .009; Cohen's d = .87], respectively. However, there was no difference between groups in M-LRN on Block 3 [t(1, 38) = .000; p = 1.00; Cohen's d = .00], indicating that after Blocks 1 and 2 (i.e., the first six sequences) both groups had learned the sequence of movements comparably. Lastly, a one-sample *t*-test comparing the mean accuracy rates of the Verbalization Only and Control groups to the mean accuracy rate of the Verbalization+Action group and the Action Only group from Experiment 1 indicated that at Block 3, performance was comparable [$t(1,39) = .975$; $p = .336$; Cohen's $d = .15$]. In summary, all three criteria which considered the sequence "learned" were met at Block 3 for both groups. Thus, we considered the trials within the first two Blocks as Learning Trials, and those within the latter three Blocks as Performance Trials.

Performance trials. As stated above, the Performance Trials consisted of the latter three Blocks. For the four motor performance variables, mean performance was calculated across the three sequence trials within each Block.

Motor planning (M-PLN). Two-group repeated measures ANOVA of M-PLN time across Performance Blocks revealed a trend towards a significant difference in performance between Groups [$F(1, 38) = 3.17$; $p = .083$, $\eta_p^2=.077$], with the Verbalization Only group showing faster mean M-PLN time across all Blocks. These findings suggest that learning the sequence verbally prior to engaging in motor action may facilitate the planning of a complex motor sequence. There was no main effect of Block [$F(2, 76) = 1.19$; $p = .282$, $\eta_p^2=.030$] and no significant Group X Block interaction [$F(2, 76) = .929$; $p = .341$, $\eta_p^2=.024$]. See Figure 4a.

Motor Control (M-CNT). Consistent with the findings from Experiment 1, two-group repeated measures ANOVA of M-CNT time across the Performance Blocks indicated that there was a trend towards a significant effect of Group [$F(1, 38) = 3.66$; $p = .063$, $\eta_p^2=.088$], with the Verbalization Only group exhibiting faster mean M-CNT time than the Control group across all performance trials. Also consistent with Experiment 1, a one-way ANOVA revealed that there were no differences between Groups on M-CNT accuracy [*F*(1, 38) = 2.54; *p* = .119; Cohen's *d* = .50], indicating that speed, but not accuracy, is improved by verbalization. There was no significant main effect of Block [*F*(2, 76) = .217; *p* = .644, η_p^2=.006] and no significant Group X Block interaction [*F*(2, 76) = .005; *p* = .944, η_p^2=.006]. See Figure 4b.

Motor set-maintenance (M-SM). Two-group repeated measures ANOVA of mean M-SM across the Performance Blocks revealed a trend towards a significant Group X Block interaction [*F*(2, 76) = 3.84; *p* = .057, η_p^2=.092], indicating that M-SM may have been affected differently across the trials depending on Group. Follow-up independent sample t-tests yielded a trend towards loss of set-maintenance for the Control group. More specifically, the Control group performed significantly worse than the Verbalization Only group on performance Block 3 (*t*(1,38) = -2.17; *p* = .036; Cohen's *d* = .69). This is despite having adequately learned the sequence across the Learning Trials. No significant main effects of Block [*F*(2, 76) = .032; *p* = .860, η_p^2=.001] or Group [*F*(1, 38) = 2.10; *p* = .156, η_p^2=.052] were found. See Figure 4c.

Performance speed (P-SPD). Two-group repeated measures ANOVA of mean P-SPD time across Performance Blocks revealed a significant main effect of Group [*F*(1, 38) = 4.49; *p* = .041, η_p^2=.106] with the Verbalization Only group performing faster across all Performance Trials than the Control group. The findings suggest that verbalization training alone facilitates performance speed. However, there was no significant Group X Block interaction [*F*(2, 76) = .887; *p* = .352, η_p^2=.023] and no significant main effect of Block [*F*(2, 76) = 1.58; *p* = .217, η_p^2=.052]. See Figure 4d.

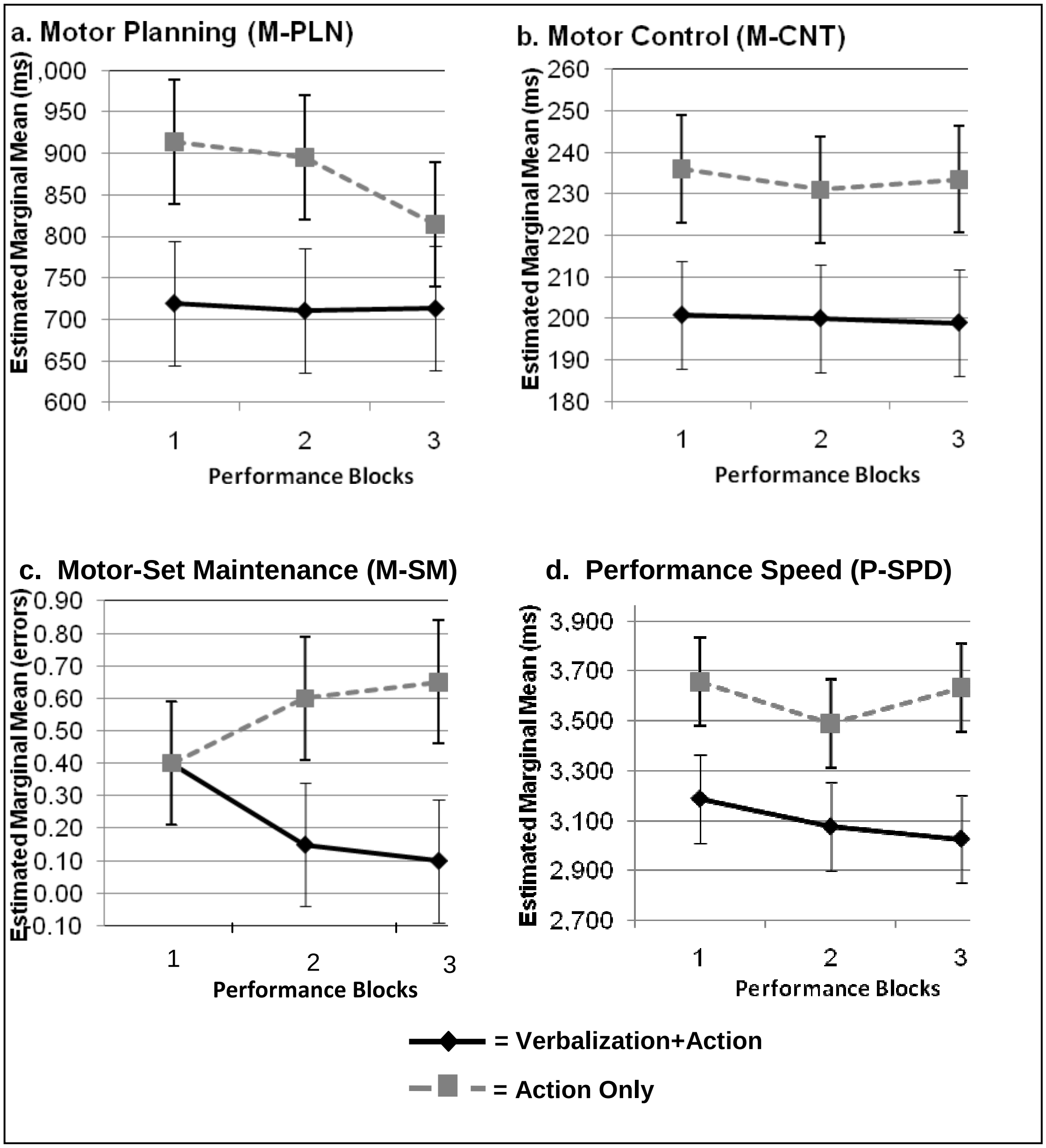

Figure 4. *Experiment 2: Performance on the Discrete Motor Components Across Performance Blocks.* Participants in the Verbalization Only group were pretrained in the sequence by verbalizing the labels of each movement (i.e., "push, turn, taptap"). Participants in the Control group received no pretraining. After completing Learning Trials all participants completed the Performance Trials, which consisted of a total of nine sequence trials. For the purpose of the statistical analyses, these nine trials were grouped into three Blocks, with each Block reflecting a mean performance value of three contiguous sequence trials. **a.** Line graph showing mean M-PLN latencies (in ms) across Performance Blocks. Analyses indicated a trend towards a significant main effect of Group (p = .077) with the Verbalization Only group showing faster mean M-PLN time across all Blocks. **b.** Line graph showing mean M-CNT latencies (in ms) across

Performance Blocks. Analyses yielded a trend towards a significant main effect of Group (p = .063), with the Verbalization Only group showing faster mean M-CNT time across all Blocks. **c.** Line graph showing mean M-SM errors across Performance Blocks. Analyses revealed a trend towards a significant Group X Block interaction (p = .057). Follow-up analyses indicated that the interaction was driven by a significant group difference on Performance Block 3 (p = .036). **d.** Line graph showing mean P-SPD time (in ms) across Performance Blocks. Analyses yielded a significant main effect of Group (p = .041), with the Verbalization Only group showing faster P-SPD across all Performance Blocks.

Figure 4. Continued.

Discussion

The findings from Experiment 2 suggest that the mere rote learning of the verbal labels of the action sequence is enough to facilitate, to some degree, all aspects of motor performance. More specifically, participants who had previous knowledge of the verbal labels of the action sequence showed a less dramatic learning curve than did the control group, indicating that verbalization facilitated the learning of the actual movements of the motor sequence. Examination of the Performance Trials revealed several trends suggesting that verbalization facilitated the planning of the action sequences, the speed and control at which discrete movements are performed, the maintenance of motor performance across trials, and the overall speed at which the movement sequence is performed.

Supplementary Analyses

Although the findings from Experiments 1 and 2 suggest that over-learning[1] the verbal labels of a sequence facilitates motor skill acquisition and performance, it remains unclear as to how much over-learning the *action* itself also contributes to improved motor performance. More specifically, both groups in Experiment 1 over-learned the action prior to performance, while neither group in Experiment 2 over-learned the action. Thus, in supplementary analyses, we compared performances in Experiment 2 to performances in Experiment 1.

[1] The term "over-learning" the sequence refers to the participants having learned the sequence well enough that it no longer needs to be held in working or short-term memory. Our learning criterion requires that participant's perform the correct sequence five times consecutively following 2 consecutive brief distraction periods.

More specifically, we conducted four repeated measures ANOVAs in which we used M-CNT, M-PLN, M-SPD, and M-SM from the performance trials of both experiments as the dependant variables. For these analyses, we created two between subjects factors that allowed us to pit Action against Verbalization across both experiments. In particular, the between subjects factors were (1) *Action* (Verbalization+Action and Action Only groups) vs. *No Action* (Verbalization Only and Control groups) and (2) *Verbalization* (Verbalization+Action and Verbalization Only groups) vs. *No Verbalization* (Action Only and Control groups). These analyses allowed us to determine whether over-learning Action, over-learning Verbalization, or interaction between the two facilitated performance.

The analyses revealed no significant main effects of Action compared to the No Action groups, and no significant interaction effects between the Action and Verbalization conditions. As expected, participants who over-learned the verbal labels of the motor sequence (i.e., the Verbalization+Action and the Verbalization Only groups) showed better performance across several of the discrete motor components compared to the No Verbalization group. More specifically, our findings suggest that over-learning the verbal labels of the motor sequence facilitates M-CNT [$F(1, 76) = 9.42$; $p = .003$, $\eta_p^2=.110$], P-SPD [$F(1, 76) = 6..68$; $p = .012$, $\eta_p^2=.081$], and to some extent M-SM [$F(1, 76) = 9.42$; $p = .091$, $\eta_p^2=.037$].

Lastly, we compared the number of trials it took the Verbalization Only group to reach the learning criterion, as compared to the Verbalization+Action and the Action Only groups There were no significant differences between learning the verbal labels alone (i.e., the Verbalization Only group[2]) or with actions (Verbalization+Action group) (Mann–Whitney U = 179.00, n_1 = 20 n_2 = 19, p = .504 two-tailed). However, participants who learned the verbal labels learned the sequence in significantly fewer trials than those participants who only learned the actions of the sequence (Action Only group), (Mann–Whitney U = 128.5, n_1 = 20 n_2 = 20, p = .008 two-tailed) and (Mann–Whitney U = 134.00, n_1 = 20 n_2 = 19, p = .040 two-tailed), respectively.

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[2] It should be noted that for the M-LRN supplementary analyses, 1 participant was removed from the Verbalization Only group due to being an extreme outlier, taking significantly more trials to learn the sequence than the rest of the group. This participant was included in all other analyses.

GENERAL DISCUSSION

To our knowledge, this is the first study to explicitly explore which aspects of motor performance are affected, whether beneficially or deleteriously, by verbalization. Using a novel motor sequence learning task, we conducted two separate experiments that allowed us to better understand how verbalization contributed to motor learning, as well as to the various aspects of motor performance once a motor sequence had been adequately learned. Experiment 1 compared motor learning and motor performance for two conditions: (a) learning motor sequence by imitation of both motor action and verbalization and (b) learning motor sequence by motor imitation *without* verbalization. Experiment 2 examined whether motor learning and performance would be facilitated by learning a sequence verbally using rote memorization (i.e., verbalization only).

As expected, the findings from both Experiments indicated that verbalization, in particular rote verbal memorization of a sequence, facilitates some aspects of motor performance regardless of whether it is combined with action or not. Interestingly, procedural (i.e., motoric) learning alone proved less efficacious than learning of the verbal labels alone. Importantly, not all aspects of motor learning and motor output are affected equally by verbalization. These findings are consistent with the literature, which has found that verbalization or explicit verbal instructions are facilitative in some, but not all, situations or populations (Anderson & Vogel, 1999; Boyd & Winstein, 2003, 2004; Landin, 1994; O'Callaghan & Couvadelli, 1998; Vintere, et al., 2004) and that various disorders show impairments in different discrete aspects of motor output (Benecke, et al.,1987; Cermak, 1985; Dewey, 2002; Dick, et al., 1986; P. D. Thompson, et al., 1988; Willingham, et al., 1997). Taken together, these findings underscore the importance of examining individual components of motor learning and motor output. The findings from both Experiments, as well as from the supplementary analyses, are summarized and discussed below.

Motor Learning (M-LRN)

M-LRN was defined as an increase in movement accuracy with practice over time (D. Willingham, 1998). Overall, the groups that over-learned the verbal labels of the sequence learned the motor sequence more quickly than their comparison groups. While this is not surprising for the Groups in Experiment 2, given that the Control group had no previous exposure to the motor sequence, it is interesting that within Experiment 1, verbalization paired with action facilitated M-LRN above and beyond just learning the sequence motorically. Our findings suggest that verbalization, regardless of whether it is paired with action or just learned via rote memorization, facilitates the M-LRN of a complex motor sequence.

The findings from the current study support previous reports, in that the use of verbalization while learning a novel complex action results in faster motor skill acquisition (Anderson & Vogel, 1999; Vintere, et al., 2004). As an extension of prior research, our study adds the interesting finding that verbalization doesn’t necessarily have to be paired with action for improved motor skill acquisition. Rather, learning the verbal labels of the action sequence via rote memorization is sufficient and facilitates motor skill acquisition. Thus, verbal rehearsal of the movement prior to even engaging in the actions will likely enhance the time in which a motor skill is initially learned.

Performance Speed (P-SPD)

Performance speed refers to the overall speed at which the entire motor sequence was performed. While in Experiment 1 there were no significant group differences on P-SPD, in Experiment 2 the Verbalization Only group performed the sequence significantly faster than did the Control group. Similarly, the supplementary analyses examining the results across both experiments indicated that those participants who were trained to use verbalization performed the entire sequence significantly faster than those who did not, regardless of whether they had the opportunity to practice the task motorically. These findings are not surprising given that P-SPD is highly correlated with the speed of the other motor variables, as well as how well the sequence was learned. More specifically, given that the participants in the Control group showed slower M-CNT, somewhat slower M-PLN, and increased errors both in the Learning and Performance Trials; it follows that their overall speed would also be slower. Taken together, it appears that P-SPD is dependent on how well the motor sequence was learned, and since verbalization appears to facilitate learning, it is likely that verbalization contributes, at least in part, to the overall speed at which a sequence can be performed.

Motor Control (M-CNT)

M-CNT refers to the correct execution of discrete movements (Whiting, et al., 1992; D. Willingham, 1998) and is considered a construct that is separate and unique from other motor output variables (Whiting et al., 1992; Suchy and Kraybill, 2007). We used the simple double tap movement (i.e., tap-tap), that is, an over-learned movement that people perform regularly throughout their life, to assess M-CNT. Despite its simplicity, this output variable seemed to be the most affected by the use of verbalization. Results from all analyses indicate that it is the memorization of the verbal labels of the sequence, rather than procedural learning of the action itself, that facilitates the smooth and rapid execution of discrete movements. These findings corroborate several earlier reports that have found that verbalization contributes to enhanced quality or execution of motor performance (Anderson, 1997; Anderson & Vogel, 1999; Janelle, et al., 2003; Landin, 1994; Mandich, et al., 2001). Further, these findings support Luria's (1959; 1961) early reports that verbalization facilitates motor control in young children, as well as in individuals with diminished capacity to internally control or regulate behavior. Lastly, these findings also support several studies that conclude that verbalization helps to control and execute action plans (Baddeley, et al., 2001; Emerson & Miyake, 2003; Goschke, 2000; Miyake, Emerson, Padilla & Ahn, 2004).

Although the current findings corroborate several other reports, past research has not addressed *why* verbalization facilitates M-CNT. Our findings, together with the recent findings of Suchy and Kraybill (2007), suggest that as working memory load increases, M-CNT is deleteriously affected. More specifically, in the Suchy and Kraybill study, participants, similar to those in our Control group (i.e., briefly exposed to verbal labels and action without the opportunity to over-learn the sequence), performed four different motor sequences, each of increasing length. The sequences were comprised of the same three movements as described in the current study. Suchy and Kraybill found that as sequence length increased (i.e., as working memory became more taxed by increasingly longer sequences), participants performed the tap-tap movement more slowly. In the current study, we found similar results, not by varying the length of the motor sequence, but by varying the access to verbal information about the motor sequence via pretraining. Specifically, in our study, those participants who had not had the opportunity to over-learn the verbal labels and thereby need to rely on working memory for performance exhibited slower M-CNT speeds than those participants who had over-learned the verbal labels of the sequence. The following interpretations can be drawn from these two studies: (a) as working memory becomes taxed (either by increased sequence length or the lack of opportunity to over-learn verbal labels), M-CNT becomes negatively affected, and (b) if the verbal labels of the sequence are over-learned, M-CNT performance significantly improves.

While more research is needed to better understand exactly *how* working memory contributes to motor control, the most likely explanation is that even simple, over-practiced and automatized movements require some level of attentional control, and this attentional control is allocated or mediated by working memory. Regardless of the exact mechanism, our findings are consistent with other reports that increased cognitive load degrades motor performance. In fact, several other studies have found that simple automatized movements (i.e., walking and balance) can be negatively affected by having participants simultaneously complete relatively simple cognitive or motor tasks (Abbud, Li & DeMont, 2009; Cherng, Liang, Hwang & Chen, 2007; Dubost, et al., 2006; Hausdorff, Yogev, Springer, Simon & Giladi, 2005; Swanenburg, de Bruin, Uebelhart & Mulder, 2009).

Motor Set-Maintenance (M-SM)

M-SM refers to the ability to maintain accurate performance once the motor sequence has been learned. The results showed that having over-learned the verbal labels (whether together with action and prior to action) helped maintain mental set. Interestingly, however, the two groups with poorer ability to maintain mental set (i.e., participants who had not over-learned the verbal labels) differed from each other in the *type* of set loss they exhibited. In Experiment 1, participants in the Action Only group showed an increase in errors immediately following the brief interruption between the Learning and Performance Trials, but then quickly returned to a level of performance that was comparable to that of the participants in the Verbalization+Action group (see Figure 3c). In contrast, in Experiment 2, the participants in the Control group initially showed comparable performance to the participants in the Verbalization Only group, but became progressively less able to maintain mental set (i.e., made more errors) across the Performance Trials (see Figure 4c). Taken together, these findings support the use of verbalization to facilitate motor set-maintenance both across a brief interruption and a shift in environment, as well as across long series of Performance Trials.

The somewhat different patterns of set loss for the two groups who did not over-learn the labels likely reflect somewhat different mechanisms. First, with regard to poorer performance of the Control group in Experiment 2, it is important to recall that the other three groups in the study (i.e., Verbalization+Action, Action Only, and Verbalization Only) were exposed to the sequence prior to the Performance Trials. The participants within these groups had the opportunity to over-learn the sequence (either verbally and/or motorically) to the point that it no longer needed to be held in working memory, as indicated by accurate performance following several distracter tasks. In other words, the information about the sequence was held in other, more permanent, memory store, from which it could be retrieved following distractions or interruptions. Since the participants in the Control group did not have the opportunity to over-learn the motor sequence (either motorically or verbally) and commit it to more permanent memory store, it is likely that they needed to hold the sequence in their working memory during execution of the Performance Trials. If that is the case, then loss of set likely reflected momentary distractions that presented themselves as the participants continued to execute the sequence. This interpretation is consistent with the notion that information stored in working memory is difficult to maintain and is easily compromised by distractions (Baddeley, 1986; Sakai & Passingham, 2004).

In contrast to the pattern exhibited by the participants in the Control group, the participants in the Action Only group from Experiment 1 showed a decrement in performance following a brief interruption in the task. This decrement occurred despite the fact that these participants had previously learned to perform the motor sequence to a predetermined learning criterion. There are several possible explanations for this loss of set. One explanation for this pattern of performance is that the participants in the Action Only group may have not automatized the task as completely as those had memorized the verbal labels and, as a result, may have been relying, at least in part, on their working memory to perform the task. If this was the case, the brief interruption in the task could have distracted the participants enough that they were no longer able to maintain the sequence in their working memory, resulting in increased errors on the initial

Performance Block. Interestingly, however, despite the initial loss of set, the participants in the Action Only group quickly regained set and performed comparably to their comparison group for the remaining trials. This pattern demonstrates that while they were distracted by the brief interruption, there was some indication that they were not completely relying on their working memory to perform the motor sequence. An alternative explanation for this pattern of performance may be that the verbal interference task performed by the participants in the Action Only group (i.e., saying "ba, ba, ba) put an increased load on working memory, above and beyond just learning the actions of the sequence. This would be consistent with the findings of Baddley et al. (2001), which showed that simultaneous verbal interference taxes working memory, which in turn slows the ability to switch between tasks. It is possible that this increased load resulted in a loss of set following the brief interruption. Further research is needed to tease these two explanations apart.

Overall, it appears that verbal rote memorization of the sequence likely facilitates the long-term storage of the motor sequence and thus a loss of set does not occur, either across performance trials or following a brief interruption in the task. Again, this suggests that over-learning the verbal labels of the sequence serves as a mechanism to enhance motor performance.

Motor Planning (M-PLN)

M-PLN refers to the internal model or action plan that precedes the correct motor commands in order to achieve the final movement goal (Buxbaum, 2005), taking into account both the movement goal and the discrete muscular movements that will be required (Keele, 1968). For this study, M-PLN was measured as the latency time that preceded the first movement of each correct action sequence. Overall, our findings provide evidence that verbalization does not facilitate M-PLN above and beyond just learning the sequence motorically. However, previous verbal knowledge of the sequence (as compared to no prior knowledge of the sequence) does seem to contribute to the speed at which a motor sequence can be planned and organized.

Although there was no main effect of verbalization (i.e., Group) on M-PLN, there was a difference in performance on the initial Performance Block for all participants in Experiment 1. More specifically, both the Verbalization+Action and the Action Only groups showed significantly slower M-PLN time in the initial Performance Trials as compared to the later trials. Interestingly, this was not the case for participants in Experiment 2. This effect is most likely associated with the brief interruption that occurred between the Learning and Performance Trials. While this brief interruption was not intended to have an effect on performance, the fact that it did provides some insight into the construct of M-PLN.

It appears that that M-PLN is more affected by task interruption than the other motor performance variables, regardless of whether or not the participants were using verbalization. In particular, in Experiment 1, the Learning and Performance Trials were separated by a brief period of interruption, during which the Performance Trials program was started and the instructions given. Immediately following this brief interruption, participants in both groups exhibited M-PLN latencies that were 1.5 to 2 times longer than those exhibited during the remainder of their performance. Given that (a) both groups had ample opportunity to practice the task prior to this interruption, and (b) their latencies appeared to reach an asymptote immediately following the initial block of

Performance Trials, it follows that the longer latencies during the initial block reflected a temporary increase in M-PLN time. This effect parallels the findings of Suchy and Kraybill (2008) that M-PLN, assessed in a manner identical to the present study, is deleteriously affected by task novelty and task complexity.

One explanation for this increase in M-PLN may be that despite the participants having over-learned the motor sequence, the task instructions introduced a perceived increase in task complexity, which deleteriously affected the M-PLN time in the initial Performance Block. A second explanation is that, perhaps, the interruption caused enough of a distraction that the participants needed to retrieve or "reactivate" the motor programs which resulted in the prolonged M-PLN time for the initial Performance Block.

Although past research has revealed reliable and robust association between M-PLN and executive functioning (Kraybill & Suchy, 2008; Suchy, et al., 2005; Suchy & Kraybill, 2007; Suchy, Kraybill & Gidley Larson, 2009; Wright, Black, Immink, Brueckner & Magnuson, 2004), our present results suggest that this association is *not* mediated by working memory. In particular, in contrast to some of the other motor output variables, M-PLN was relatively *un*affected by memorization of the sequences verbally. In other words, freeing up working memory by prior memorization did not improve the M-PLN time. Thus, although increases in sequence length have been shown to require increases M-PLN latencies (Suchy & Kraybill, 2007), this effect likely cannot be explained by increases in working memory load.

Clinical Implications

Verbalization has been used across various populations in rehabilitation, despite a lack of clear understanding of exactly how it contributes to M-LRN and to the other discrete components of motor performance. Although the current study provides insight into the contributions of verbalization to the discrete components of motor learning and performance, which can help inform some aspects of cognitive and motor rehabilitation, more research is needed in this area. The direct implications of the current study to clinical populations are summarized and discussed briefly below.

First, verbalization does not have to be paired with action in order to facilitate some aspects of motor performance. In fact, verbal rote memorization of the action sequence prior to performance appears to be sufficient to improve motor accuracy, learning, control, and speed. This finding is consistent with O'Callaghan and Couvadelli’s (1998) report that the memorization of verbal scripts helped ameliorate executive and visuomotor impairment, as well as facilitated motor skill transfer in three patients with TBI. Our findings suggest that the use of this declarative cognitive strategy may be helpful for individuals who have difficulties with procedural learning, individuals who have impairments in the frontal networks which help with the initial learning of motor sequences, or those individuals with specific impairments in M-CNT or M-LRN.

Second, verbalization may facilitate various aspects of motor output by reducing the load placed on the frontal networks, particularly by decreasing the reliance on working memory. This finding is particularly important for individuals with immature or damaged frontal brain regions and would be consistent with Luria’s findings that verbalization facilitates motor control in young children, as well as in individuals with diminished capacity to internally control or regulate behavior (1959; 1961). Further, recent research indicates that individuals with Huntington’s disease have difficulty achieving automaticity in their movements, due to increased demands placed on their frontal networks (Thompson, et al., 2009); it is possible that over-learning the verbal labels of the action sequence via rote memorization prior to performance may improve movement automaticity. Thus, in a sense the use of verbalization may help those who have difficulty encoding information procedurally.

Lastly, while not specific to verbalization, our study shows that disruption or interruption slows the time in which someone is able to plan and prepare a subsequent motor action. This finding is consistent with a large body of research on switching costs incurred during switching from one action to another (Hyafil, Summerfield & Koechlin, 2009; Monsell, 2003). Given that these findings were from healthy college-aged adults with no apparent weaknesses or impairments, it is likely that interruptions are very costly for individuals with limited resources. Therefore, it is important to limit interruptions and distractions when working with clinical populations.

LIMITATIONS AND FUTURE DIRECTIONS

Although the findings of the current study are interesting and have clinical implications, replication of the findings is important, particularly in various patient populations. Given that our findings suggest that verbalization facilitates motor performance by decreasing the load on working memory, future studies should include populations with executive and attentional impairments as well as various age cohorts. Additionally, future research should have an increased number of Performance Trials in order to better understand how verbalization contributes to performance over time. Lastly, future research should examine the mechanisms by which verbalization, particularly verbal rote memorization, facilitates motor performance. By gaining more understanding of these underlying processes we will be able to better inform cognitive and motor rehabilitation.

SUMMARY

This is the first study to examine the contribution of verbalization to motor learning and to the discrete components of motor performance. Overall, our study indicates that verbalization facilitates (1) the initial learning of a complex motor sequence, (2) the speed of execution of simple discrete movements, (3) the maintenance of performance over time, and (4) to some degree the overall speed at which a motor sequence is performed. While our findings corroborate previous research, our study adds to this body of research with the findings that (a) verbalization does not have to be paired with action to facilitate performance and (b) that mere rote memorization of the verbal labels of the motor sequence facilitates many aspects of performance above and beyond learning the sequence motorically. Further, while much more research is needed to fully understand this relationship, our findings suggest that over-learning the verbal labels of the sequence serves as a mechanism to enhance motor performance, particularly with regard to the speed and control of discrete movements and the maintenance of performance overtime. More specifically, it appears that over-learning the verbal labels of the sequence contributes by decreasing the load placed on working memory and by initiating a faster transition of the motor sequence from short to long-term memory. Lastly, our findings have direct implications for cognitive and motor rehabilitation in clinical populations.

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