Does limiting pre-movement time during practice eliminate the benefit of practicing while expecting to teach?

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ABSTRACT

Past research has revealed practicing and studying a motor skill with the expectation of teaching it to another person increases the amount of time participants spend preparing for movement during practice trials of the skill. However, it is unknown whether the increased motor preparation time explains the benefit of expecting to teach on motor learning. To address this question, we had participants practice golf putting with the expectation of teaching the skill to another participant the following day or the expectation of being tested on the skill the following day. We limited the motor preparation time for half of the participants who expected to teach and half of the participants who expected to test, and allowed the remaining participants to take as much motor preparation time as they liked. All participants were tested on their putting the next day. We predicted that participants who expected to teach would exhibit superior posttest performance, but this benefit would be exclusive to those participants who also practiced with unlimited motor preparation. Although the current data did not support this hypothesis, we also conducted an exploratory analysis in which we aggregated data from two prior experiments. This cumulative analysis suggested that expecting to teach does indeed enhance motor learning, but not through motor preparation during practice.

1. Introduction

Determining practical ways to enhance motor learning is critical to improve motor behavior. Past research has shown that practicing and studying a motor skill with the expectation of teaching it to another person enhances skill learning relative to practicing and studying with the expectation of being tested (Daou, Buchanan, Lindsey, Lohse, & Miller, 2016; Daou, Lohse, & Miller, 2016, 2018). Specifically, participants expecting to teach have demonstrated superior skill accuracy and precision, as well as declarative knowledge about the skill, when assessed during posttests 1-day and 7-days after practice. Initially, researchers believed the benefit of expecting to teach could be attributed to heightened motivation and/or pressure during practice (Daou, Buchanan et al.,

2016). In particular, it was reasoned that expecting to teach should cause a learner to recognize that their own learning may affect another person's learning, thereby increasing their drive and pressure to learn. Elevated motivation and pressure (stress) while practicing and studying, in turn, could yield psychological and physiological states conducive for learning (e.g., increased dopaminergic activity [Arnsten, 2009; Wulf & Lewthwaite, 2016]), thereby revealing a 'direct' effect of expecting to teach on motor learning. Heightened motivation and stress could also prompt learners to engage in additional practice trials or study time, consequently, enhancing learning; thus demonstrating an 'indirect' effect of expecting to teach on motor learning. However, neither motivation nor pressure have been demonstrated to increase as a function of expecting to teach (Daou, Buchanan et al., 2016; Daou, Lohse, Buchanan, & Miller, 2016; Daou, Lohse, & Miller, 2018).[1]

Beyond motivation and pressure, Daou, Lohse, et al. (2016) examined whether enhanced information processing during practice and studying could explain the benefit of expecting to teach. The authors reasoned that expecting to teach may cause a learner to process more information about the skill they are practicing and studying, knowing that they will have to communicate this information to another person, and that greater information processing should improve learning (Cross, Schmitt, & Grafton, 2007). The authors used the amount of time spent in motor preparation before each practice trial (pre-movement time) as a proxy for information processing. Results revealed expecting to teach lengthened pre-movement time and predicted posttest accuracy and precision. However, pre-movement time did not predict posttest accuracy and precision when controlling for whether participants expected to teach, thus casting doubt on whether increased motor preparation explains the expecting to teach effect or merely coincides with it. In a follow-up experiment, Daou et al. (2018) used electroencephalography (EEG) to examine cerebral cortical dynamics during the final 3 s of motor preparation before each practice trial and did not observe any effects of expecting to teach. The authors concluded the benefit of expecting to teach might be explained by the duration of motor preparation, but not the cortical dynamics during preparation.

The present experiment aimed to test whether motor preparation contributes to the advantage of expecting to teach. Specifically, we had participants practice golf putting with the expectation of teaching the skill to another participant the following day or the expectation of being tested on the skill the following day. We limited the motor preparation time for half of the participants who expected to teach and half of the participants who expected to test, and allowed the remaining participants to take as much motor preparation time as they deemed necessary. All participants were tested on their putting the next day. We predicted an expectation by motor preparation interaction revealing that the benefit of expecting to teach on posttest accuracy and precision would be exclusive to those participants who also practiced with unlimited motor preparation.

2. Methods

Prior to beginning data collection, the experimental design and analyses were registered and made public on AsPredicted.org (https://aspredicted.org/rhc5n.pdf).

2.1. Participants

Eighty right-handed young adults (54 females, M_{age} = 21.8, SD = 2.52 years; see Table 1 for descriptive data) completed the experiment after providing informed written consent to a research protocol (Protocol #14-534 EP 1412) approved by Auburn University's Institutional Review Board. Participants were recruited from university courses and by word-of-mouth. They were compensated with entry into a raffle for a monetary award and course credit, if enrolled in an eligible course. Sample size was determined with an a priori power calculation using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). The power calculation sought 80% power ($\alpha \leq 0.05$) to detect moderate-sized effects (f^2 = 0.15) of expectation, motor preparation, and an Expectation × Motor Preparation interaction on posttest accuracy/precision in a multiple linear regression model. The model included three other predictors: pretest accuracy/precision, number of putts taken during practice, and amount of time spent studying during practice.

2.2. Task

Participants used a standard, right-handed golf putter to putt a standard golf ball on an artificial grass surface to a target cross (+) comprised of two 10.8 cm pieces of white masking tape located 120 cm from a starting position, which was indicated by a 5 cm piece of white masking tape next to participants. The objective was to have the ball stop as close to the center of the target as possible.

2.3. Procedure

All participants completed the experiment individually. After consenting to the experiment, they completed a demographic questionnaire asking their age, sex, and putting experience (anything from miniature golf to playing 18 holes on a standard golf course) over their lifetime and within the past year.

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[1] As for additional practice trials or study time, Daou, Buchanan et al. (2016) did not observe an effect of expecting to teach, and Daou, Lohse et al. (2016) only observed expecting to teach increased study time. In both experiments, the number of putts and study time failed to predict posttest accuracy or precision.

Table 1
Descriptive data for each group.

Group:	Test Limited (n = 21; 14 females)		Teach Limited (n = 19; 14 females)		Test Unlimited (n = 20; 13 females)		Teach Unlimited (n = 20; 13 females)	
	M	CI (95%)	M	CI (95%)	M	CI (95%)	M	CI (95%)
Descriptive Data by Group								
Age (years)	20.9	20.3–21.4	22.3	20.5–24.2	21.1	20.3–22.0	22.9	20.9–24.8
Lifetime Putting Experience[a]	1.38	0.98–1.77	1.63	1.17–2.09	1.40	0.98–1.81	1.15	0.80–1.49
Past-Year Putting Experience[a]	0.476	0.243–0.708	0.368	0.130–0.606	0.500	0.260–0.740	0.450	0.211–0.688
Studying (s)	203	162–243	227	183–270	212	169–254	258	205–310
Putts	54.2	49.1–59.3	55.4	50.5–60.2	57.1	50.1–64.2	58.7	50.1–67.3
Intrinsic Motivation	5.38	4.93–5.82	5.37	4.96–5.77	5.37	4.85–5.88	5.49	4.97–6.00
Internalized Motivation	6.00	5.60–6.39	5.69	5.21–6.16	5.95	5.52–6.37	5.73	5.29–6.16
General Motivation	5.40	4.90–5.89	5.09	4.53–5.64	5.57	5.13–6.00	5.50	5.03–5.96
Pressure	2.37	1.86–2.87	2.40	2.02–2.77	2.33	1.81–2.84	2.11	1.73–2.48
Free Recall	2.52	2.12–2.91	3.05	2.55–3.54	1.90	1.29–2.50	2.85	2.26–3.43
Pre-Movement Time (s)	–	–	–	–	6.05	4.28–7.81	5.88	4.49–7.27

[a] 0 = Never putted; 1 = Putted 1–10 times; 2 = Putted 11–20 times; 3 = Putted 21–30 times.

2.3.1. Pretest

After completing the demographic questionnaire, participants were asked to perform the pretest phase. Pretest consisted of one block of ten putts. As the purpose of this phase was to determine participants' baseline skill level, we attempted to isolate performance and minimize on-line learning by preventing participants from using feedback about the outcome of their putts. To this end, participants wore a blindfold and earplugs while putting (Dyke et al., 2014). Participants were permitted to view the ball and the target after the experimenter reset the ball in the starting position. Once the participant placed the putter behind the ball, they pulled down their blindfold before putting. Further, the experimenter waited 45 s after each putt to reset the ball in the starting position. In so doing, participants could not determine their accuracy by how quickly the experimenter reset the ball. (High accuracy could be inferred from a quick reset, since the experimenter manually measured the distance of the ball to the target before manually resetting the ball in the starting position, making measurement quicker for putts closer to the target.)

2.3.2. Practice

After pretest, participants were read instructions according to the groups to which they were randomly assigned. Participants in the teach groups (n = 39) were told "tomorrow you will teach another participant how to putt," and participants in the test groups (n = 41) were told "tomorrow you will be tested on your putting." Next, participants were told they had 1 h to learn how to putt, and they had to remain in the experiment laboratory for the duration of the hour. To initiate the practice phase, participants studied a golf putting instruction booklet for at least 2 min; however, it was emphasized that they could take as long as they liked. The instructions for the booklet were provided by an expert golfer (for booklet, see Daou, Buchanan et al., 2016). After studying the booklet, participants were told they would be performing at least five blocks of ten putts, but they could take additional putts if they wanted. Between each block, participants were told they had a 1 min break during which they could study the booklet if they wanted. Participants who chose to continue practicing for 10 blocks were then cut off from taking any additional putts, or further study time of the manual.

During the practice phase, 20 of the participants in the teach group and 20 of the participants in the test group had unlimited motor preparation time before each putt (the time from when the experimenter reset the ball until the participant began their next putt), yielding a teach unlimited and test unlimited group. The remaining participants had their motor preparation time limited during practice, yielding a teach limited (n = 19) and test limited (n = 21) group. Specifically, the experimenter told participants in these groups:

> "After I put the ball on the ground, at the starting position, you will only have a few seconds to putt before a tone is played. If you don't begin your backswing before the tone, then I will pick up the ball, and you will start the trial over again. So you must putt the ball before the tone is played. Your goal is to make the ball stop as close to the target as you can."

On each trial of the practice phase, the experimenter placed the ball at the starting position and asked participants to affirm being ready to putt. Upon participant affirmation, the experimenter pressed a button on a keyboard for a computer located ~150 cm behind participants, which elicited a tone (750 Hz and 90 dB) from speakers adjacent to the computer at a random interval 4–5 s after the keypress. The 4–5 s motor preparation time limit was based on Daou, Lohse, et al. (2016), who observed 27 out of 28 participants in the teach group took at least 5 s to putt. Thus, imposing this motor preparation time limit should have caused teach participants to take less time preparing their movements than they otherwise would have. Pre-movement time was recorded (30 frames/s) with a video camera (Logitech C930e, Logitech International, Newark, CA) focused on the starting position during odd-numbered blocks for all participants, but we were only interested in the preparation time for the teach/test unlimited groups, which we expected to significantly differ as in Daou, Lohse et al.

Immediately after participants reported that they were done putting or completed 100 putts, they filled out the Intrinsic Motivation Inventory (IMI) (McAuley, Duncan, & Tammen, 1989) to assess whether expectation and/or preparation time influenced motivation and/or pressure. The subscales of interest were as follows: interest/enjoyment, value/usefulness, effort/importance, and pressure/tension. Examples of each subscale of interest are as follows: interest/enjoyment item, "I enjoyed doing this activity very much"; value/usefulness item, "I think this is an important activity"; effort/importance item, "I put a lot of effort into this activity"; pressure/tension item, "I was anxious while working on this activity". The questionnaire was scored on a seven-point Likert scale with "not true at all" and "very true" as the anchors. (The perceived competence and perceived choice subscales were also collected, but they were not analyzed, as these subscales are merely correlates of motivation, and it is motivation that is more directly linked to motor learning [Wulf & Lewthwaite, 2016]).

2.3.3. Posttests (retention and transfer)

Approximately 24 h after completing Day 1, participants returned to complete the experiment. Participants in the teach groups were told, "the participant who you were going to teach did not show up today, so you will actually be tested on your putting instead." Next, all participants completed the retention test and transfer test in a counterbalanced order. For the retention test, participants putted to the same target as during pretest and practice, whereas for the transfer test they putted to a target located 170 cm away. As with the pretest, we sought to minimize online learning during the posttest, so participants were blindfolded and ear-plugged and the amount of time between putts was fixed at 45 s. After the retention and transfer tests, we assessed participants' declarative knowledge by asking them to complete a free recall test wherein they were asked to "…report, in as much detail as possible, any rules, methods, or techniques [they recalled] using to execute putts during practice on the first day of the study" (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Finally, participants were debriefed about the purpose of the experiment, and teach participants were told that they were deceived into expecting to teach another participant and asked if they still wanted to have their data included in the experiment. (They all did.)

2.4. Data processing

2.4.1. Performance and learning

Putting accuracy and precision were measured because they are separate and critical aspects of motor learning (Fischman, 2015). Specifically, accuracy was indexed by recording radial error as recommended by Hancock, Butler, and Fischman (1995): *Radial Error* $(RE) = (x^2 + y^2)^{1/2}$, where $\times$ and y represent the magnitude of error along the respective axes (i.e., how far away from the target cross the ball stopped in the horizontal and vertical directions). Precision was indexed by recording bivariate variable error as recommended by Hancock et al.: *Bivariate Variable Error* $(BVE) = \left\{ \left(\frac{1}{k}\right) \sum_{i=1}^{k} [(x_i - x_c)^2 + (y_i - y_c)^2] \right\}^{1/2}$, where k = trials in a block and $_c$ = centroid along the given axis (x or y) for that block. RE and BVE were calculated for pretest to assess baseline skill level, odd-numbered blocks of the practice phase for a glimpse into practice performance without overly slowing data collection, and retention and transfer tests to measure learning.

2.4.2. Pre-movement time

The duration from when the experimenter placed the ball in the starting position to when the participant began the putting movement was determined via frame-by-frame analysis of the video recorded during the first, third, and fifth acquisition blocks. The first putt of each of these blocks was excluded from analysis, because participants were often reorienting themselves to the task, asking the experimenter a question, etc. (Daou, Lohse, et al., 2016).

2.4.3. Free recall

To measure declarative knowledge (free recall), the number of key concepts from the putting instruction booklet correctly re-called by participants was recorded. The key concepts are the most important concepts, as indicated by the expert golfer who provided the putting instructions: (1) "establish proper grip," (2) "place the putter head behind the ball and take a hip-width stance," (3) "place the eyes directly over the ball by hinging from the hips," and (4) "stroke the ball without breaking the wrists" (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018).

2.4.4. IMI processing

IMI subscales exhibited good reliability: interest/enjoyment (Chronbach's $\alpha = 0.917$), value/usefulness (Chronbach's $\alpha = 0.877$), effort/importance (Chronbach's $\alpha = 0.849$), and pressure/tension (Chronbach's $\alpha = 0.739$). Thus, scores were averaged within subscales.

2.4.5. Skill study and practice putts

The amount of time participants spent looking at the putting instruction booklet was recorded in order to quantify the amount of time they spent studying the skill during the practice phase. Specifically, during the initial study phase of at least 2 min, a researcher controlled a chronometer on a computer located < 2 m from the participant. The researcher used the chronometer to record the time the participant was looking at the booklet, as opposed to looking elsewhere. After the initial 2 min, the researcher told the participant that the "two minutes time is over, but you may study the booklet for as long as you want." When participants told the researcher that

they were done studying, the researcher recorded the final study time for the initial study phase. During the 1 min breaks between acquisition blocks, the researcher used the chronometer to record the amount of time the participant spent looking at the instruction booklet. The initial study time was then combined with the between-blocks study time to yield the 'studying' variable. (It is possible participants were studying by mentally rehearsing putting instructions without looking at the booklet, but we unable to include this form of studying in our 'studying' variable.) The number of putts they took during the practice phase was recorded to quantify their practice repetitions; this variable is referred to as 'putts'. Studying and putts were used to examine the 'indirect' effect of expecting to teach on motor learning.

2.5. Statistical analysis

To measure motor learning, multiple linear regressions for RE and BVE, each averaged across retention and transfer tests, were conducted[2]. The first step in each regression included the following variables: pretest RE or BVE, putts, and studying. The second step of each regression included the following variables: expectation (test/teach) and motor preparation (limited/unlimited). The third step of each regression included the interaction term: Expectation × Motor Preparation.

To measure practice performance, mixed-factor ANCOVAs were conducted for RE and BVE: 2 (Expectation) × 2 (Motor Preparation) × 3 (Practice Block: 1/3/5), with repeated measures on the last factor and pretest RE or BVE serving as the covariate.

IMI subscales, studying, putts, and free recall were submitted to 2 (Expectation) × 2 (Motor Preparation) between-subjects ANOVAs. Pre-movement time was submitted to an independent sample t-test (Expectation) for the groups with unlimited motor preparation.

Alpha levels were set to 0.05 for all tests, and the Greenhouse-Geisser correction is provided when sphericity was violated. The p-values reported are based on the corrected degrees of freedom. Results will be reported beginning with mechanistic variables and free recall, followed by practice performance, and then posttest performance.

3. Results

3.1. Primary analyses (Current Sample)

3.1.1. Studying, putts, motivation, pressure, pre-movement time, and free recall

No effects of expectation ($ps \geq 0.106$), motor preparation ($ps \geq 0.333$), or Expectation × Motor Preparation ($ps \geq 0.605$) were found for studying or putts (see Table 1). Similarly, no effects of expectation ($ps \geq 0.207$), motor preparation ($ps \geq 0.218$), or Expectation × Motor Preparation ($ps \geq 0.569$) were found for measures of motivation or pressure. For free recall, a main effect of expectation was observed f ($F(1, 76) = 10.9$, $p = .004$, $\eta_p^2 = .102$), but there were no effects of motor preparation or Expectation × Motor Preparation ($ps \geq 0.105$). There was no effect of expectation on pre-movement time ($p = .877$)[3]. In sum, these results replicate prior work in showing a strong effect of expecting to teach on free recall, but not on studying, putts, motivation, or pressure (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Notably, that expecting to teach did not increase pre-movement time is in contrast to Daou, Lohse, et al. (2016).

3.1.2. Practice performance

Fig. 1A shows accuracy (RE) for the groups across all phases of the study. During practice, there were no effects of expectation ($p = .575$), motor preparation ($p = .210$), block ($p = .657$), Expectation × Motor Preparation ($p = 0.990$), Expectation × Block ($p = .630$), Motor Preparation × Block ($p = .180$), or Expectation × Motor Preparation × Block ($p = .880$) on RE, controlling for pretest RE. Fig. 1B depicts precision (BVE) for groups across all phases of the study. During practice, there were no effects of expectation ($p = .580$), block ($p = .855$), Expectation × Motor Preparation ($p = .580$), Expectation × Block ($p = .606$), or Expectation × Motor Preparation × Block ($p = .470$) on BVE, controlling for pretest BVE. However, there were significant effects of motor preparation ($F(1, 75) = 5.42$, $p = .023$, $\eta_p^2 = .067$) and Motor Preparation × Block ($F(1.16, 87.1) = 3.82$, $p = .048$, $\eta_p^2 = .048$). Follow-up univariate ANCOVAs (motor preparation) for each block (controlling for pretest BVE) revealed participants with limited motor preparation exhibited superior precision for block 1 ($M_{adjusted} = 31.6$ cm, $CI_{95\%} = 22.1$–41.1 cm) relative to their counterparts with unlimited motor preparation ($M_{adjusted} = 46.6$ cm, $CI_{95\%} = 37.2$–56.1 cm), but motor preparation time did not affect precision for blocks 3 ($p = .313$) or 5 ($p = .221$). In summary, practice performance results replicate prior findings that

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[2] To justify averaging across retention and transfer tests for RE and BVE, we preceded the regressions with mixed-factor ANCOVAs: 2 (Expectation) x 2 (Motor Preparation) x 2 (Posttest: retention/transfer), with repeated-measures on the last factor. Pretest RE or BVE, studying, and putts served as covariates, and RE or BVE served as the dependent variable. Since posttest did not interact with either expectation or motor preparation ($ps \geq 0.257$), we were statistically justified in averaging across the retention and transfer tests in order to reduce the number of regressions we conducted (Lohse et al., 2016). From a motor learning perspective, we had no reason to predict expecting to teach would affect learners' retention of a skill differently than it would affect their ability to generalize the skill to a new parameter (target distance). Therefore, from a theoretical standpoint, we also thought it was best to average across the retention and transfer tests in order to reduce the number of regressions we conducted.

[3] It is worth noting that the 95% CI for pre-movement time for the test unlimited and teach unlimited groups includes the average pre-movement time limitation placed on the test limited and teach limited groups (4.5 s). Thus, it is possible the pre-movement time for the test limited and teach limited groups was not very limiting. However, this is an irrelevant point since additional analyses (see Section 3.4) indicate pre-movement time is not related to motor learning and, thus, likely does not contribute to the advantage of practicing with the expectation of teaching.
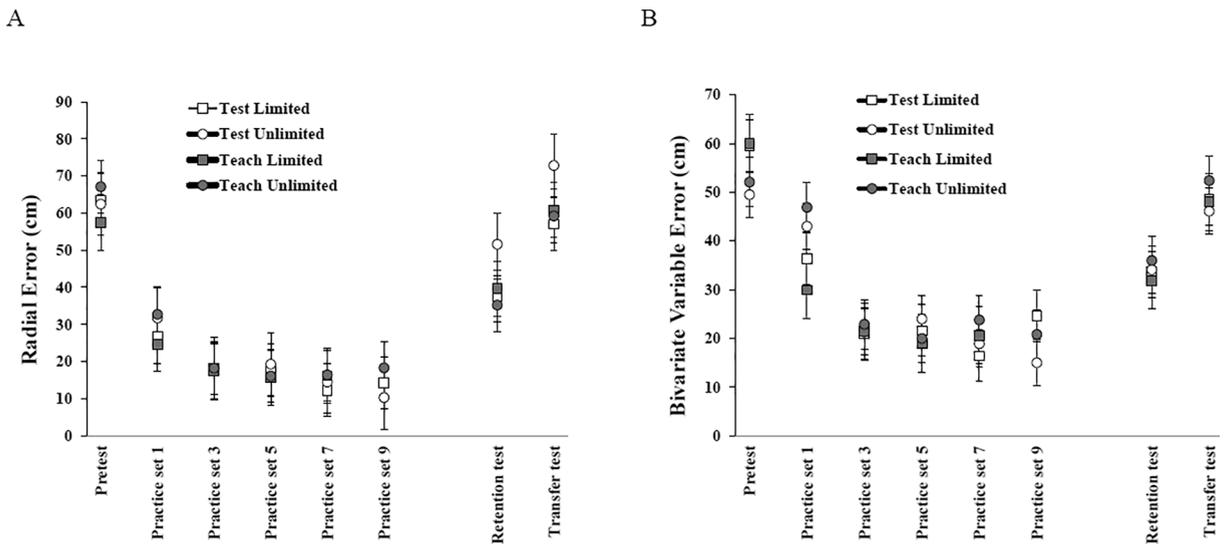
A

B

Fig. 1. A) Putting accuracy (lower RE indicates greater accuracy) as a function of study phase and group. B) Putting precision (lower BVE indicates greater precision) as a function of study phase and group. All error bars represent 95% *CIs*.

expecting to teach does not influence practice accuracy or precision (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018), and indicate limiting motor preparation time may have a benefit to precision on early practice trials.

3.1.3. Posttest performance

The first step of the regression predicting posttest RE revealed pretest RE to be a significant predictor ($ß_{pretest}$ = 0.284 cm, p = .004), but neither studying (p = .605) or putts (p = .693) were significant predictors (see Table 2). The second step of the regression added expectation and motor preparation, neither of which were significant predictors (ps = 0.469 and 0.417, respectively). The final step of the regression added Expectation × Motor Preparation, but this interaction term was not a significant predictor (p = .139).

The first step of the regression predicting posttest BVE revealed pretest BVE to be a significant predictor ($ß_{pretest}$ = 0.184 cm, p = .001), but neither studying (p = .860) nor putts (p = .703) were significant predictors (see Table 3). The second step of the regression added expectation and motor preparation, neither of which were significant predictors (ps = 0.712 and 0.307, respectively). The final step of the regression added Expectation × Motor Preparation, but this interaction term was not a significant predictor (p = .479).

Although expectation and motor preparation time did not affect posttest performance, it is worth noting that participants generally did exhibit motor learning. Specifically, a 2 (Expectation) × 2 (Motor Preparation) × 3 (Test: pretest/retention test/transfer test) ANOVA with repeated-measures on the latter factor for RE shows a main effect of test ($F(1.41, 107)$ = 16.9, p < .001, η_p^2 = .182, Greenhouse-Geisser correction ε = 0.703). Follow-up paired sample *t*-tests demonstrate participants were significantly more accurate on the retention test than the pretest ($t(79)$ = 5.01, p < .001, d = 0.630) and on the retention test than the transfer test ($t(79)$ = 7.81, p < .001, d = 0.570). Participants also got more precise from pretest to posttest, as revealed by a 2 (Expectation) × 2 (Motor Preparation) × 3 (Test) ANOVA with repeated-measures on the latter factor for BVE, which shows a main effect of test ($F(1.33, 101)$ = 25.8, p < .001, η_p^2 = .253, Greenhouse-Geisser correction ε = 0.665). Follow-up paired sample *t*-tests demonstrate participants were significantly more precise on the retention test than the pretest ($t(79)$ = 6.37, p < .001, d = 0.762) and on the retention test than the transfer test ($t(79)$ = 8.87, p < .001, d = 0.793).

In summary, expectation, motor preparation, and Expectation × Motor Preparation did not predict posttest accuracy or precision, neither of which were predicted by studying or putts. Expectation not predicting posttest accuracy and precision is inconsistent with past studies (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Given this null result, we conducted a cumulative analysis of the current data combined with past work.

3.2. Exploratory analysis (cumulative analysis of past and present expecting to teach experiments)

3.2.1. Posttest Performance

The present results differ in a few ways from other results our laboratory has published (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Specifically, present results did not reveal a main effect of expecting to teach on RE and BVE (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018) nor did present results reveal a main effect of expecting to teach on pre-movement time (Daou, Lohse, et al., 2016). Notably, these experiments sampled from similar populations in terms of age, sex, and putting experience (college-age males and females with little putting experience). To determine whether differences in results can be attributed to sampling variability or failed replication, we combined the present data from participants whose motor

Table 2

Details of regression models testing the hypotheses that expectation, motor preparation, and Expectation × Motor Preparation predict posttest RE.[a]

Model 1: Avg. Retention and Transfer Test RE ~ Pretest + Studying + Putts

	SS	Df	MS	F	R^2 Change
Regression	9452	3	3151	3.31	0.116
Residual	72,292	76	951		

Coefficients	β	CI	*t*-value	*p*-value
Intercept	44.3	11.77–76.8	2.71	0.008
Pretest RE	0.284	0.095–0.474	2.99	0.004
Studying	−0.020	−0.098–0.058	0.520	0.605
Putts	−0.104	−0.626–0.418	0.396	0.693

Model 2: Avg. Retention and Transfer Test RE ~ Pretest + Studying + Putts + Expectation + Motor Preparation

	SS	Df	MS	F	R^2 Change
Regression	10,594	5	2119	2.20	0.014
Residual	71,150	74	961		

Coefficients	β	CI	*t*-value	*p*-value
Intercept	45.2	12.0–78.3	2.72	0.008
Pretest RE	0.277	0.086–0.468	2.89	0.005
Studying	−0.017	−0.097–0.063	0.421	0.675
Putts	−0.125	−0.653–0.402	0.473	0.638
Expectation	−2.57	−9.62–4.47	0.727	0.469
Motor Preparation	2.86	−4.12–9.84	0.817	0.417

Model 3: Avg. Retention and Transfer Test RE ~ Pretest + Studying + Putts + Expectation + Motor Preparation + Expectation x Motor Preparation

	SS	Df	MS	F	R^2 Change
Regression	12,709	6	2118	2.24	0.026
Residual	69,036	73	946		

Coefficients	β	CI	*t*-value	*p*-value
Intercept	44.2	11.3–77.1	2.68	0.009
Pretest RE	0.285	0.095–0.474	2.99	0.004
Studying	−0.015	−0.094–0.065	0.366	0.715
Putts	−0.124	−0.647–0.400	0.471	0.639
Expectation	−2.61	−9.60–4.38	0.743	0.460
Motor Preparation	2.69	−4.24–9.62	0.774	0.441
Expectation x Motor Preparation	−5.16	−12.0–1.72	1.50	0.139

[a] Regression coefficients are not standardized and are thus interpretable in their natural units. For expectation, test is coded as '−1' and teach as '1'. For motor preparation, limited is coded as '−1' and unlimited as '1'. CI is 95%.

preparation time was unlimited with data from Daou, Buchanan et al. (2016) and Daou, Lohse, et al. (2016). Both of these prior experiments used the same task, blindfolded/ear-plugged pretests and 1 day posttests, allowed the amount of study time and putts to vary, and permitted unlimited motor preparation time. (Daou et al. (2018) used longer putt distances, did not use a blindfold/earplugs, and fixed the amount of study time and putts.) Table 4 summarizes the results of Daou, Buchanan et al. and Daou, Lohse et al.

For RE and BVE, we conducted 3 (Experiment: Daou, Buchanan et al./Daou, Lohse et al./Present Experiment) × 2 (Expectation) × 2 (Posttest) mixed factor ANCOVAs, with the final factor serving as a repeated-measure. We controlled for pretest RE or BVE, studying, and putts. For RE, results showed a main effect of expectation ($F(1, 143) = 21.8$, $p < .001$, $\eta_p^2 = 0.132$), with the teach group exhibiting lower RE ($M_{\text{adjusted}} = 41.6$ cm, $CI_{95\%} = 34.9$–48.4 cm) than the test group ($M_{\text{adjusted}} = 64.6$ cm, $CI_{95\%} = 57.8$–71.4 cm). Notably, the Experiment × Expectation interaction was not significant ($F(2, 143) = 0.502$, $p = .607$, $\eta_p^2 = .007$). Thus, these results suggest the effect of expecting to teach on RE did not significantly differ among the present experiment and prior experiments, which, together, reveal a significant effect of expecting to teach (see Fig. 2A). Accordingly, the nonsignificant effect in the present experiment is likely due to sampling variability.

For BVE, results showed a main effect of expectation ($F(1, 143) = 17.4$, $p < .001$, $\eta_p^2 = .108$), with the teach group exhibiting lower BVE ($M_{\text{adjusted}} = 37.8$ cm, $CI_{95\%} = 34.4$–41.2 cm) than the test group ($M_{\text{adjusted}} = 48.0$ cm, $CI_{95\%} = 44.6$–51.4 cm). However, this effect was superseded by a significant Experiment × Expectation interaction ($F(2, 143) = 6.52$, $p = .002$, $\eta_p^2 = .084$) (see Fig. 2B). Thus, these results suggest either (a) the significant effect of expecting to teach on BVE in the prior experiments were false

Table 3

Details of regression models testing the hypotheses that expectation, motor preparation, and Expectation × Motor Preparation predict posttest BVE.[a]

Model 1: Avg. Retention and Transfer Test BVE ~ Pretest + Studying + Putts

	SS	Df	MS	F	R^2 Change
Regression	3093	3	1031	4.67	0.156
Residual	16,773	76	221		

Coefficients	β	CI	t-value	p-value
Intercept	33.1	17.7–48.6	4.27	< 0.001
Pretest BVE	0.184	0.080–0.289	3.50	0.001
Studying	0.003	−0.034–0.040	0.177	0.860
Putts	−0.048	−0.297–0.201	0.383	0.703

Model 2: Avg. Retention and Transfer Test BVE ~ Pretest + Studying + Putts + Expectation + Motor Preparation

	SS	Df	MS	F	R^2 Change
Regression	3359	5	672	3.01	0.013
Residual	16,507	74	223		

Coefficients	β	CI	t-value	p-value
Intercept	34.0	18.3–49.6	4.33	< 0.001
Pretest BVE	0.194	0.087–0.301	3.61	0.001
Studying	0.000	−0.039–0.038	0.021	0.984
Putts	−0.057	−0.308–0.194	0.454	0.652
Expectation	0.631	−2.76–4.02	0.371	0.712
Motor Preparation	1.76	−1.65–5.16	1.03	0.307

Model 3: Avg. Retention and Transfer Test BVE ~ Pretest + Studying + Putts + Expectation + Motor Preparation + Expectation x Motor Preparation

	SS	Df	MS	F	R^2 Change
Regression	3473	6	579	2.58	0.006
Residual	16,393	73	225		

Coefficients	β	CI	t-value	p-value
Intercept	34.1	18.4–49.8	4.33	< 0.001
Pretest BVE	0.194	0.087–0.301	3.60	0.001
Studying	−0.001	−0.040–0.037	0.061	0.951
Putts	−0.056	−0.308–0.195	0.447	0.656
Expectation	0.643	−2.76–4.04	0.377	0.707
Motor Preparation	1.79	−1.63–5.21	1.05	0.299
Expectation x Motor Preparation	1.20	−2.15–4.54	0.711	0.479

[a] Regression coefficients are not standardized and are thus interpretable in their natural units. For expectation, test is coded as '−1' and teach as '1'. For motor preparation, limited is coded as '−1' and unlimited as '1'. CI is 95%.

positive results, or (b) the nonsignificant effect of expecting to teach on BVE in the present experiment is a false negative result. Given that significant effects were observed in the two experiments included in this cumulative analysis as well as Daou et al. (2018), it seems more likely that the nonsignificant effect of expecting to teach on BVE in the present experiment is a false negative.

3.2.2. Pre-movement time

When taken together, results from the present experiment and three others published by our laboratory suggest expecting to teach improves posttest RE as well as BVE. However, the mechanisms underlying these effects remain unclear. Daou, Lohse, et al. (2016) proposed that pre-movement time may be an underlying mechanism based on their observation that expecting to teach increased pre-movement time, which predicted posttest RE and BVE. However, the present experiment did not show this effect. To address this inconsistency, we combined data from Daou, Lohse et al. and the present experiment, and conducted a 2 (Experiment) × 2 (Expectation) between-subjects ANOVA with pre-movement time serving as the dependent variable. (Again, we only included participants from the present experiment whose preparation time was unlimited.) Results revealed a significant effect of expectation ($F(1, 91) = 7.73$, $p = .007$, $\eta_p^2 = .078$), such that participants who expected to teach exhibited longer pre-movement time ($M = 7.37$ s, $CI_{95\%} = 6.55$–8.19 s) than participants who expected to test ($M = 5.73$ s, $CI_{95\%} = 4.90$–6.57 s). However, this main effect was superseded by an Experiment × Expectation interaction ($F(1, 91) = 9.38$, $p = .003$, $\eta_p^2 = .093$) (driven by the significant effect of expectation in Daou, Lohse et al. and nonsignificant effect of expectation in the present experiment). Thus, there is no consistent effect of expectation on pre-movement time.

Table 4

Statistical tests for Daou, Buchanan et al. (2016) and Daou, Lohse, et al. (2016)[a.]

Daou, Buchanan et al. (2016)	F	$Df_{numerator}$	$Df_{denomenator}$	p
Radial Error				
Expectation	11.1	1	51	0.002
Posttest	3.73	1	51	0.059
Expectation × Posttest	0.597	1	51	0.443
Bivariate Variable Error				
Expectation	16.6	1	51	< 0.001
Posttest	2.85	1	51	0.098
Expectation × Posttest	0.903	1	51	0.347
Daou, Lohse, et al. (2016)[b]				
Radial Error				
Expectation	9.93	1	51	0.003
Posttest	5.46	1	51	0.023
Expectation × Posttest	0.661	1	51	0.420
Bivariate Variable Error				
Expectation	13.7	1	51	0.001
Posttest	1.22	1	51	0.274
Expectation × Posttest	3.16	1	51	0.081
Pre-Movement Time	t	Df	p	
Expectation	5.34	54	< 0.001	

[a] Statistical tests were ANCOVAs with posttest radial error and bivariate variable serving as dependent variables. These ANCOVAs were conducted as 2 (Expectation: test/teach) × 2 (Posttest: retention/transfer), with repeated-measures on the second factor. Covariates were pretest radial error or bivariate variable error, studying, and putts. An independent sample *t*-test (expectation) was conducted for pre-movement time.
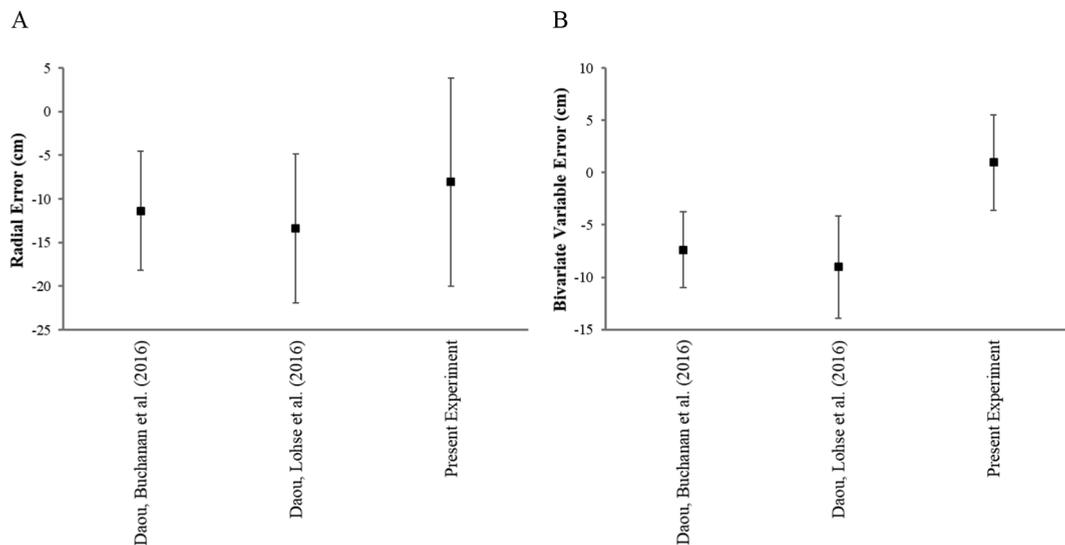
Fig. 2. Unstandardized beta coefficient of the effect of expecting to teach on posttest (avg. retention and transfer test) RE (Panel A) and BVE (Panel B) in three experiments. Coefficients are based on a model accounting for pretest RE or BVE, studying, and putts. Negative numbers represent positive effects (reduced error) in favor of the expecting to teach group (contrast coded as '1' relative to the expecting to test group, which is coded as '−1'), and error bars represent 95% *CI*s.

Next, we investigated whether increased pre-movement time is even a candidate for explaining the learning benefit of expecting to teach. In order to be a candidate, pre-movement time should predict learning, irrespective of experimental manipulation (expectation to teach/test). Thus, we used the data from Daou, Lohse, et al. (2016) and the present experiment to address this issue. (Again, we only included participants from the present experiment whose preparation time was unlimited.) Specifically, we conducted a multiple linear regression to predict posttest RE averaged across retention and transfer tests. The first step of the regression included the following variables: pretest RE, expectation, studying, and putts; and the second step of the regression added motor preparation time. Results showed pre-movement time did not predict posttest RE ($p = .843$). A similar regression predicting posttest BVE also showed a null effect for pre-movement time ($p = .139$). Thus, pre-movement time in our golf putting paradigm does not seem to predict posttest RE or BVE. This suggests the significant relationship between pre-movement time and RE as well as BVE observed by Daou, Lohse et al. was simply due to participants who expected to teach exhibiting long pre-movement time *coincident* to

low RE and BVE. Taken together, results from the cumulative pre-movement time analyses suggest that even if expecting to teach does increase pre-movement time, this increase does not explain the learning benefit of expecting to teach.

4. Discussion

4.1. Present experiment

The present experiment tested the hypothesis that increased motor preparation time preceding practice trials explains the motor learning benefit of practicing a skill with the expectation of teaching it to another person. Specifically, motor preparation time during practice was limited for approximately half of the participants who practiced with the expectation of teaching, and statistical tests examined whether the benefit of expecting to teach on posttest accuracy (RE) and precision (BVE) was eliminated for these participants.

In the present experiment, expecting to teach did not enhance posttest accuracy or precision, and our attempt to limit motor preparation time did not affect posttest accuracy or precision. Although it is possible we did not sufficiently limited motor preparation time, this variable does not appear to be related to posttest accuracy or precision, so it is unlikely expecting to teach could benefit motor learning by increasing preparation time. Expecting to teach enhanced free recall of putting techniques at posttest, replicating prior experiments and indicating expecting to teach enhances declarative knowledge (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018).

The present experiment revealed that expecting to teach does not enhance motivation or pressure during practice, which is consistent with past experiments (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Additionally, the present experiment failed to reveal expecting to teach enhances the duration of motor preparation during practice, which is inconsistent with Daou, Lohse, et al. (2016).

4.2. Cumulative analysis

We conducted cumulative analyses by combining datasets from two other published experiments in our laboratory (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016) with data from the present experiment. Results from this analysis suggest the effect of expecting to teach on posttest accuracy in the present experiment was within the range of sampling variability, albeit non-significant. There are multiple ways to judge replication success, beyond statistical significance, including whether the confidence interval of the present effect includes the effect obtained in past experiments (Open Science Collaboration, 2015). As such, we do not consider the present experiment a failed replication, but the underlying effect size of expecting to teach on posttest accuracy is likely smaller than originally estimated.

Results from the cumulative analysis suggest the null effect of expecting to teach on posttest precision in the present experiment is indeed a failed replication: The effect was not significant in the present experiment, and the confidence interval of the effect does not include the effects observed in prior experiments. However, we believe the present result is likely a false-negative given that the only three other published experiments investigating the expecting to teach effect have shown a benefit to posttest precision (Daou, Buchanan et al., 2016; Daou, Lohse, et al., 2016; Daou et al., 2018). Cumulatively then, we believe evidence suggests expecting to teach enhances motor learning, as measured by posttest accuracy and precision.

The cumulative analysis suggests expecting to teach enhances motor learning, but these experiments provide little insight into the mechanisms underlying this effect. Importantly, a cumulative analysis of Daou, Lohse, et al. (2016) and the present experiment suggests motor preparation time does not predict posttest accuracy or precision, thereby making it unlikely that motor preparation time explains the learning benefit of expecting to teach. Further, when one considers Daou et al. (2018) observed expecting to teach does not influence cerebral cortical dynamics during motor preparation while practicing, it appears expecting to teach does not affect information processing during motor preparation, at least in the ways by which we have measured motor preparatory information processing.

Thus, the question of what mechanisms underlie the motor learning benefit of expecting to teach remains open. One possibility is that expecting to teach affects neurocognitive processes at the end of each practice trial rather than at the beginning (during motor preparation). Specifically, successful practice trials may be more rewarding to participants who practice with the expectation of teaching relative to their counterparts who practice with the expectation of being tested. This could be the case if participants who expect to teach place more emphasis on successful outcomes knowing that they will have to teach another participant how to achieve such outcomes. If participants who expect to teach find successful practice trials highly rewarding, then they will experience large positive reward-prediction errors (RPEs) and phasic increases in dopaminergic activity after successful practice trials (Wulf & Lewthwaite, 2016). These enhanced RPEs and dopaminergic responses can facilitate consolidation of the movement patterns that produced the successful trial. Future research may investigate the possibility that expecting to teach enhances learning by amplifying RPEs, specifically by indexing RPEs to augmented feedback about practice trial outcome with the EEG-derived reward positivity component of the event-related potential waveform (Grand, Daou, Lohse, & Miller, 2017). Additionally (or alternatively), participants who expect to teach may pay closer attention to trial outcomes knowing that they will have to teach another participant how to achieve successful outcomes. This enhanced attention to trial outcomes could also be investigated by indexing processing of augmented feedback with EEG (Grand et al., 2015).

5. Conclusion

In conclusion, cumulative analyses suggest practicing a motor skill with the expectation of teaching it to another person appears to enhance learning, as indexed by skill accuracy and precision on delayed posttests as well as declarative knowledge about the skill. The learning effects on skill accuracy and precision do not appear to be related to motor preparatory processes, motivation, or pressure during practice, leaving the mechanisms underlying the benefit of practicing with the expectation of teaching unknown. Thus, we suggest instructors have learners practice with the expectation of teaching, and researchers attempt to elucidate mechanisms underlying the beneficial effects of such practice.

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