THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2017
http://dx.doi.org/10.1080/17470218.2016.1276204

Routledge
Taylor & Francis Group

Triple play: Additive contributions of enhanced expectancies, autonomy support, and external attentional focus to motor learning

Gabriele Wulf[a], Rebecca Lewthwaite[b,c], Priscila Cardozo[d] and Suzete Chiviacowsky[d]

[a]Department of Kinesiology and Nutrition Sciences, University of Nevada, Las Vegas, NV, USA; [b]Physical Therapy Department, Rancho Los Amigos National Rehabilitation Center, Downey, CA, USA; [c]Division of Biokinesiology and Physical Therapy, University of Southern California, Las Vegas, CA, USA; [d]Department of Physics, Federal University of Pelotas, Pelotas, Brazil

ABSTRACT
In the OPTIMAL theory of motor learning [Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-015-0999-9], 3 factors are postulated to facilitate learning: enhanced expectancies (EE) for performance, autonomy support (AS), and an external focus (EF) of attention. In 3 recent studies, combinations 2 of these variables resulted in superior learning relative to the presence of only 1 variable, or none. We examined whether the combination of all 3 factors would enhance learning relative to combinations of 2 factors. Our design included EE–AS, EE–EF, AS–EF, and AS–EE–EF groups. Participants threw balls at a target with their non-dominant arm. In the EE conditions, they received positive social–comparative feedback. In the AS conditions, they were allowed to throw with their dominant arm on trial blocks chosen by them. In the EF conditions, participants were asked to focus on the target. On a delayed retention test, the AS–EE–EF group outperformed all other groups. The findings provide evidence that enhanced expectancies, autonomy support, and an external focus can contribute in an additive fashion to optimize motor learning.

ARTICLE HISTORY
Received 16 January 2016
Accepted 13 December 2016

KEYWORDS
Choice; Dopamine; Motor performance; Throwing

Three key variables for optimal motor learning have recently been identified (Wulf & Lewthwaite, 2016): two motivational variables (i.e., enhanced expectancies for positive experience or outcomes, including performance, and autonomy) and one attentional variable (i.e., external focus of attention). Learner expectancies can be enhanced in various ways. In several studies, *enhanced expectancies* resulted from feedback that was provided on trials with relatively small errors rather than larger errors; as a consequence, learning was facilitated (e.g., Badami, VaezMousavi, Wulf, & Namazizadeh, 2012; Chiviacowsky & Wulf, 2007; Clark & Ste-Marie, 2007; Saemi, Porter, Ghotbi-Varzaneh, Zarghami, & Maleki, 2012). Also, (false) positive social–comparative feedback, which led learners to believe that their performance was superior to that of their peers, has been found to enhance motor learning (e.g., Ávila, Chiviacowsky, Wulf, & Lewthwaite, 2012; Lewthwaite & Wulf, 2010). Even statements suggesting that peers typically do well on a task to be learned (Wulf, Chiviacowsky, & Lewthwaite, 2012, Experiment 2) or increasing learners' perceptions of success during practice (Chiviacowsky & Harter, 2015; Chiviacowsky, Wulf, & Lewthwaite, 2012; Palmer, Chiviacowsky, & Wulf, 2016; Trempe, Sabourin, & Proteau, 2012) can be sufficient to promote learning.

Autonomy is another motivational variable that appears to be important for optimal learning. Practice conditions that support learners' need for autonomy—typically termed self-controlled practice in the motor learning literature (for a review, see Sanli, Patterson, Bray, & Lee, 2013)—have consistently been shown to positively affect motor skill learning. For instance, allowing learners to control the delivery

CONTACT Gabriele Wulf gabriele.wulf@unlv.edu Department of Kinesiology and Nutrition Sciences, University of Nevada, 4505 Maryland Parkway, Las Vegas, NV, USA

of feedback (Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997), use of assistive devices (e.g., Hartman, 2007; Wulf & Toole, 1999), extent of practice (Post, Fairbrother, Barros, & Kulpa, 2014), and frequency of skill demonstrations (e.g., Wulf, Raupach, & Pfeiffer, 2005), among other factors, results in more effective learning. These findings likely have motivational underpinnings (Lewthwaite & Wulf, 2012). Being autonomous, or having the ability to control one's own actions, is a fundamental psychological need (Deci & Ryan, 2000, 2008). Conditions in which autonomy support is conveyed through choice or language have been shown to increase individuals' motivation and performance or learning (e.g., Reeve & Tseng, 2011; Wulf, Freitas, & Tandy, 2014). Importantly, even incidental choices that are not directly related to task performance have been shown to provide learning benefits (e.g., Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015; Wulf, Chiviacowsky, & Cardozo, 2014). For example, in the Lewthwaite et al. (2015) study (Experiment 1), allowing participants to choose the colour of golf balls led to more effective learning of a putting task than not giving them that choice.

Finally, adopting an *external focus of attention* (i.e., a focus on the intended movement effect) has consistently been shown to enhance learning compared with an internal focus on body movements or no instructed focus (control conditions; for reviews, see Lohse, Wulf, & Lewthwaite, 2012; Marchant, 2011; Wulf, 2013). Concentrating on the planned effect of one's movements (e.g., on an implement) enhances movement effectiveness (e.g., balance, accuracy, consistency) and efficiency (e.g., force production, muscular activity, heart rate, oxygen consumption). An external focus promotes automaticity relative to a focus on body movements (Wulf, McNevin, & Shea, 2001). The effect of greater automaticity is better movement fluidity (Kal, van der Kamp, & Houdijk, 2013), increased use of reflexive movement adjustments (e.g., McNevin, Shea, & Wulf, 2003), and more effective dual-task performance (e.g., Kal et al., 2013). Thus, an external focus enhances motor control processes and, in turn, learning—independent of the task, performer's skill level, age, or (dis)ability. In effect, by adopting an external focus, a higher skill level is reached in less time (Land, Frank, & Schack, 2014; Wulf, 2007).

While each of the three factors individually have been shown to enhance learning, three recent studies examined whether combining two factors—enhanced expectancies and autonomy support (Wulf, Chiviacowsky et al., 2014), enhanced expectancies and an external focus (Pascua, Wulf, & Lewthwaite, 2015), or autonomy support and an external focus (Wulf, Chiviacowsky & Drews, 2015)—would result in additional benefits relative to the presence of only one of these factors, or none. In each study, additive effects of two factors were found. That is, the presence of each pairing of two factors produced a greater learning benefit compared with only one. These findings suggest that enhanced expectancies, autonomy support, and an external focus assist learning through at least (partially) different pathways or mechanisms.

In the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016), we proposed that the three factors—enhanced expectancies (EE), autonomy support (AS), external focus (EF)—each contribute to skill learning. The effects of autonomy, however, were proposed to be partially mediated by enhanced expectancies, as were those of an external attentional focus. Empirically, it has been shown that autonomy-supportive conditions can affect self-efficacy expectations (e. g., Hooyman, Wulf, & Lewthwaite, 2014; Wulf, Chiviacowsky et al., 2014, 2015). Likewise, for attentional focus and expectancies, the successful performance created from an external focus can influence self-efficacy, likely through the performance accomplishment route (e.g., Bandura, 1977; Pascua et al., 2015). While these investigations on a psychological/behavioural level of analysis indicate the shared relations described above, they also indicate that not all of each variable's effects are funnelled or absorbed through the others. For example, self-efficacy boosts from an external attentional focus appeared in one study to account for a portion of the attentional focus influence on learning (Pascua et al., 2015). We can think of no reason, however, why autonomy would directly affect attentional focus, or that the opposite would be true.

While the empirical findings to date and the behavioural level of analysis can support the relationships and non-relationships described above, another relevant influence on our additive models pertains to the hypothesized relationships of expectancies and anticipated autonomy to underlying neural activity and dopamine responses (described in Wulf & Lewthwaite, 2016). At this neural level, dopamine neurons are found in multiple sites in the spatially extensive corticomesolimbic system and may contribute reward-relevant performance boosts and learning-relevant consolidation effects from multiple locations (Brown, McCutcheon, Cone, Ragozzino, & Roitman, 2011; Saddoris, Sugam, Cacciapaglia, & Carelli, 2013; Saddoris et al., 2015). Distinct sites may relate to autonomy and to success expectations (DePasque & Tricomi, 2015; Lee & Reeve, 2013), aspects consistent with separable (additive) effects. In addition to our behavioural studies described above, neural examinations indicate that the effects of some expectancy-relevant variables (e.g., monetary rewards and positive affect) are additive, with the addition of positive affect to a reward condition boosting neural activity in relevant regions (e.g., Murayama et al., 2015; Widmer, Ziegler, Held, Luft, & Lutz, 2016; Young & Nusslock, 2016).

Thus, we predicted that the presence of all three factors would yield even more effective learning than practice conditions that include only two factors (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015). The present study was designed to test this assumption. Practice of a novel motor task (i.e., throwing at a target with the non-dominant arm) included combinations of two factors for three groups (EE–AS, EE–EF, AS–EF), as in the previous studies (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015), and all three factors for the fourth group (EE–AS–EF). We hypothesized that the last group would show more effective learning than the other three groups. Motor learning, defined as relatively permanent changes in the ability to produce a motor skill (R. A. Schmidt & Lee, 2011), is typically measured by delayed retention (or transfer) tests (e.g., Winstein & Schmidt, 1990). Group differences on those tests reflect the (relative) learning resulting from different practice conditions.

Experimental study

Method

Participants

Sixty university students (40 males, 20 females), with a mean age of 22.8 years ($SD = 3.87$), participated in the study. None of them was ambidextrous (3 were left-handed). All were naïve as to the purpose of the experiment. Before participating in the study, all participants signed an informed consent form, which was approved by the university's institutional review board.

Apparatus and task

Participants' task was to throw beach-tennis balls (5.5 cm in diameter with 50% of the pressure of regulation tennis balls) overhand with their non-dominant arm at a target. The target consisted of a bull's eye and was hung in a net ($2.4 \times 2.4 \times 1.0$ m) 7.5 m from the participant. The centre of the bull's eye was 1.2 m above the ground. The bull's eye had a 10-cm radius and was surrounded by nine concentric circles. The concentric circles had radii of 20, 30, 40, . . . and 100 cm. If the ball hit the bull's eye, 100 points were awarded by the experimenter. Ninety points were given for hitting the next circle, and so forth. If a ball hit a line separating two zones, the higher score was awarded. Throws that completely missed the target were given 0 points. A video camera recorded all throws, and the recordings were later used to determine the exact score if there was uncertainty during the testing session.

Procedure

Participants were first given basic instructions for the overhand throw with the non-dominant arm (e.g., stay behind the line, throw with the left arm, take a step forward with the right foot) and a demonstration by the experimenter. Handedness was determined by asking participants which hand they typically used to throw balls. Participants then performed a pre-test consisting of five trials. This was followed by the practice phase, which consisted of six blocks of 10 practice trials. Participants received feedback about their average accuracy score after each block of 10 trials. Participants were randomly assigned to one of four groups: enhanced expectancy and autonomy support (EE–AS), enhanced expectancy and external focus (EE–EF), autonomy support and external focus (AS–EF), and enhanced expectancy, autonomy support, and external focus (EE–AS–EF). Performance expectancies were enhanced (in the EE–AS, EE–EF, EE–AS–EF groups) by providing positive social–comparative feedback, in addition to veridical scores after each 10-trial block. The social–comparative feedback was a bogus score, allegedly the average score that participants in previous experiments had produced on the respective block. It was 20% lower than the participant's score. Thus, participants were led to believe that their performance was above average (cf. Lewthwaite & Wulf, 2010). In the autonomy-supportive conditions (EE–AS, AS–EF, EE–AS–EF group), participants were able to choose four blocks of five trials in which they could use their dominant arm. In the EE–EF group, the only group without autonomy support, participants were yoked to participants in the EE–AS–EF group with respect to the blocks in which they used their dominant arm. Finally, in the external focus conditions (EE–EF, AS–EF, EE–AS–EF groups), participants were asked to focus on the target. They were reminded to maintain that focus before each 10-trial block. Participants were informed, before the beginning of practice, that they would only use their non-dominant arm on Day 2. On the following day, participants performed a retention test consisting of 10 trials. They used only their non-dominant arm on the retention test, and they were not given feedback or attentional focus reminders. The experimenter was not blind to condition, but was not familiar with the experimental hypotheses.

Data analysis

To determine whether dominant-hand use across practice was comparable for the various groups, we counted the average number of blocks during the first and second halves of practice in which participants in each group used their dominant arm. Throwing accuracy scores were averaged across five (pre-test) or 10 trials (practice, retention), respectively. The pre-test data were analysed in a one-way analysis of variance (ANOVA). The practice data were analysed in a 4 (groups) × 6 (blocks of 10 trials) ANOVA with repeated measures on the last factor. Planned comparisons were used to analyse the retention test data. Based on previous findings (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015) suggesting that each variable made unique contributions to learning, we predicted that the EE–AS–EF group would outperform all other groups on the retention test. In addition, we compared the groups' relative improvement from the pre-test to the retention test in a 4 (groups) × 2 (test) repeated measures ANOVA.

Results

Dominant-arm use

The four blocks of five trials on which participants used their dominant arm were distributed similarly across groups. Generally, the frequency was somewhat higher in the first half of practice. The EE–AS–EF and (yoked) EE–EF groups had an average of 2.2 dominant-arm blocks in the first and 1.8 in the second half of the practice phase, while the EE–AS and AS–EF groups both had an average of 2.4 and 1.6 blocks in the first and second halves, respectively.

Pre-test

All groups had similar accuracy scores on the pre-test (see Figure 1). There were no differences among groups, $Fs(3, 56) = 0.296$, $p = .828$.

Practice

During the practice phase, throwing accuracy generally increased across blocks. The main effect of block, $F(5, 280) = 3.96$, $p = .002$, $\eta_p^2 = .07$, was significant. The group main effect was not significant, $F(3, 56) = 1.37$, $p = .262$. There was no interaction of group and block, $F(15, 280) = 0.594$, $p = .879$.

Retention

Planned comparisons for the retention test revealed that throwing accuracy was significantly higher for the EE–AS–EF condition ($M = 39.2$, $SD = 11.7$) than for the EE–AS ($M = 31.7$, $SD = 16.3$), AS–EF ($M = 25.2$, $SD = 14.0$), and EE–EF ($M = 31.5$, $SD = 14.0$) conditions, $t(56) = 2.32$, $p = .024$, 95% confidence interval, CI [28.22, 35.55]. Thus, learning was enhanced by the presence of all three factors relative to only two. This learning advantage for the EE–AS–EF group was confirmed by the fact that this group was the only one that showed higher throwing accuracy on the retention test ($M = 39.2$) than on the pre-test ($M = 30.8$). The interaction of group and test was significant, $F(3, 56) = 2.92$, $p = .042$, $\eta_p^2 = .02$. Post hoc tests indicated that the change in performance was significant for the EE–AS–EF group, $p = .023$, but not for the EE–AS, $p = .204$, AS–EF, $p = .115$, and EE–EF groups, $p = .941$. The main effects of group or test were not significant, $Fs < 1$.

General discussion

Enhanced expectancies, autonomy support, and an external focus of attention are considered key factors in a new theory of motor learning (Wulf & Lewthwaite, 2016). Previous behavioural studies have provided initial support for this supposition by showing that combinations of two of these factors enhanced learning relative to the presence of only one, or none, of these factors (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015). In the present study, we went one step further by testing the hypothesis that having all three factors present during practice would further facilitate learning compared with two factors. In line with our hypothesis, a practice condition that incorporated enhanced expectancies,

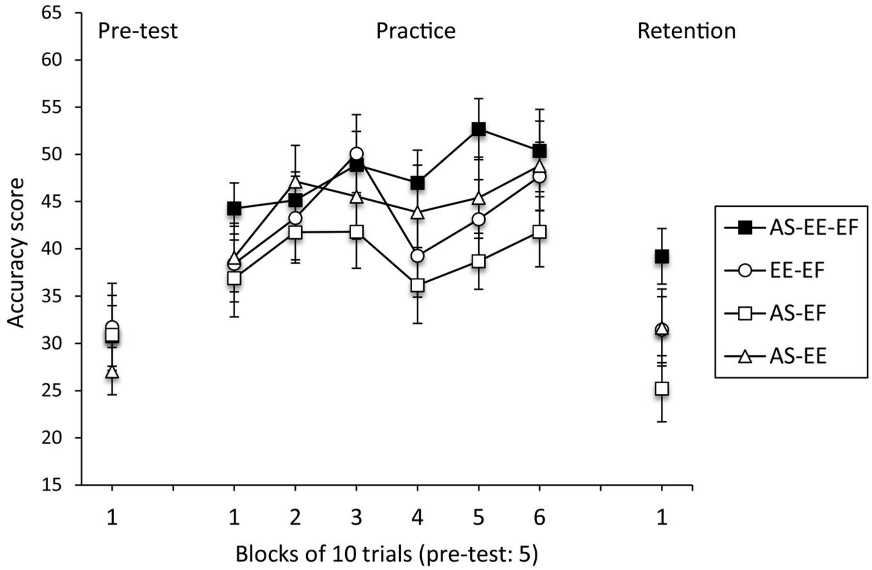

Figure 1. Throwing performance of the four groups on the pre-test, during practice (Day 1), and on the retention test (Day 2). Error bars indicate standard errors. EE = enhanced expectancies; AS = autonomy support; EF = external focus.

autonomy support, and an external focus resulted in more effective learning than did all other conditions that included only two of these variables. The EE–AS–EF group outperformed all the other groups on the retention test and was the only group that demonstrated an improvement in accuracy relative to pre-test performance.

While it might seem surprising that retention scores were generally relatively low, particularly when compared with end-of-practice and pre-test performance, this pattern of results appears to be typical for the type of task we used (throwing with the non-dominant arm). Previous studies found similar results (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015). We suspect that throwing accuracy would likely have increased quickly had the retention test included more trials. Indeed, Janelle et al. (1997), who used the same task with two days of practice and a retention test on a third day, found similar drop-offs in performance at the beginning of Days 2 and 3. Yet, the accuracy levels seen on previous days were reached and exceeded quickly with further trials. Low scores at the beginning of a new (practice or retention) session can reflect warm-up decrement. Other possible explanations for the low accuracy in retention exist as well. For example, participants were informed that they now had to use their non-dominant arm on all trials—which might have been perceived as a more controlling situation, with consequences for performance. Importantly, though, the predicted relative group differences emerged on the retention test.

Interestingly, the three conditions that included two factors produced similar learning effects, irrespective of which factors they included. Such may be the case because the motivational factors may provide the expectation of rewarding experiences to affect neural activation and dopaminergic response, and attentional focus facilitates task success and may directly and indirectly (through enhanced expectancies) influence brain responses to affect motor learning. Dopaminergic response is a plausible mechanism, associated with additive or dose-response effects, memory consolidation, and neural pathway development (e.g., Dayan & Cohen, 2011; Wise, 2004), though we did not examine it directly here. An interesting corollary of the dopaminergic explanation is that dopamine can be widely and diversely elicited within the mesocorticolimbic reward system to affect performance and learning (Braver et al., 2014; Brown et al., 2011; Saddoris et al., 2013, 2015). Although previous work has not examined the dopaminergic dynamics of multiple motivational triggers, it is perhaps more likely that an additive rather than threshold effect might be found. In the threshold situation, dopamine from any source might suffice and block further effects from other sources. Our findings are consistent with a cumulative or additive effect, whether attributable or not to underlying dopaminergic responses.

What do enhanced expectancies, autonomy support, and an external attentional focus contribute to learning that makes them valuable? Enhanced expectancies both portend and prepare individuals for further positive outcomes or experiences and have impacts on cognitive, emotional, and motor preparatory activity (Bandura, 1977; L. Schmidt, Braun, Wager, & Shohamy, 2014; Wulf, Chiviacowsky et al., 2012). For example, performance expectancies influence goal setting (Locke & Latham, 2006) and task enjoyment (Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008), and increase positive affect (Pascua et al., 2015; Stoate, Wulf, & Lewthwaite, 2012). Enhanced expectancies may also serve as a buffer against responses that would detract from optimal performance, such as off-task activity (cf. Jiao, Du, He, & Zhang, 2015; Zahodne, Nowinski, Gershon, & Manly, 2015) or self-referential processing (e.g., McKay, Wulf, Lewthwaite, & Nordin, 2015). Conceptually, high performance expectancies appear to prepare the performer for successful movement, ensuring that goals are effectively coupled with desired actions (Wulf & Lewthwaite, 2016).

The exercise of control appears to provide an inherent reward (Karsh & Eitam, 2015; Leotti & Delgado, 2011). Eitam, Kennedy, and Higgins (2013) demonstrated that the perception that one's actions have effects on the environment is important for motivation. Support for an individual's autonomy may heighten a sense of personal agency (Chambon & Haggard, 2012) and personal expectations for positive outcomes (e.g., Chiviacowsky, 2014; Hooyman et al., 2014; Wulf, Chiviacowsky et al., 2014, 2015). Thus, one role of autonomy support may be to facilitate learning indirectly by enhancing performers' expectancies. A second possibility concerns a potential role for autonomy/sense of agency in assisting in the triggering of switches between neural networks needed for given task success. A number of studies localize the neural substrate of a sense of personal agency and self-determination in the anterior insula (Lee & Reeve, 2013; Sperduti, Delaveau, Fossati, & Nadel, 2011), a cortical structure with a potentially important function supporting efficient goal–action coupling for performance and learning (Menon, 2015; Wulf & Lewthwaite, 2016). Thus, autonomy support might indirectly (through enhanced expectancy) and directly through support for efficient goal–action coupling, benefit performance and learning.

Finally, an external attentional focus can play a dual role by (a) directing attention to the task goal and (b) reducing a focus on the self (see self-invoking trigger hypothesis; McKay et al., 2015; Wulf & Lewthwaite, 2010). Both appear to be necessary for optimal performance. As demonstrated in a recent study by Russell, Porter, and Campbell (2014), an external focus on the primary task (dart throwing) was necessary to enhance performance, whereas an external focus on a simultaneously performed secondary task—which should have directed attention away from the self—was not sufficient to enhance performance (similar to internal foci on either task). By ensuring a focus on the task goal, an external focus directly connects goals and actions. Furthermore, by reliably producing more successful performance outcomes, an external attentional focus contributes to the success that enhances expectations (Pascua et al., 2015; Rosenqvist & Skans, 2015; Shafizadeh, Platt, & Bahram, 2013). As noted earlier, expectations for positive outcomes and experience are associated with dopaminergic responses supportive of learning.

Wulf and Lewthwaite (2016) posited that practice under optimal motivational (enhanced expectancy, autonomy support) and attentional focus (external focus) conditions facilitates the development of more effective neural connections that support motor performance and learning. Motor learning is associated with changes in structural connectivity as well as in functional connections across brain regions. Enhanced performance expectancies and learner autonomy and an external focus of attention direct movers with relative clarity toward their action goals—thereby promoting functional connectivity, a hallmark of expert performance (e.g., Kim, Han, Kim, & Han, 2015; Kim et al., 2014). Functional connectivity refers to temporal linkages between spatially separated brain regions that occur during task performance (Friston, 2011). Low-level oscillatory resonance of activity patterns in functionally connected brain regions can also be observed at rest when regions have operated in concert. Reward-related dopamine boosts the replay of memories during rest that contribute to consolidation (Ewell & Leutgeb, 2014).

While we await direct neuroscientific evidence for the proposed mechanisms of enhanced expectancies, learner autonomy, and an external focus of attention, behavioural findings have presented a fairly clear picture. Each factor independently has been shown to lead to more effective learning than its absence in numerous studies. Combinations of two factors have produced additive benefits for learning in each case (Pascua et al., 2015; Wulf, Chiviacowsky et al., 2014, 2015). Finally, as the present study demonstrates, the presence of all three factors can lead to even greater learning benefits than each combination of two factors. To optimize motor skill learning in practical settings, instructors may take advantage of these effects by, for example, highlighting positive aspects of performance and ensuring that success can be experienced, giving learners choices to support their need for autonomy and finding appropriate external foci for a given task or level of expertise.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ávila, L. T. G., Chiviacowsky, S., Wulf, G., & Lewthwaite, R. (2012). Positive social-comparative feedback enhances motor learning in children. *Psychology of Sport and Exercise*, *13*, 849–853.

Badami, R., VaezMousavi, M., Wulf, G., & Namazizadeh, M. (2012). Feedback about more accurate versus less accurate trials: Differential effects on self-confidence and activation. *Research Quarterly for Exercise and Sport*, *83*, 196–203.

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review*, *84*, 191–215.

Braver, T. S., Krug, M. K., Chiew, K. S., Kool, W., Westbrook, J. A., Clement, N. J., … Somerville, L. H. (2014). Mechanisms of motivation-cognition interaction: Challenges and opportunities. *Cognitive, Affective, & Behavioral Neuroscience*, *14*, 443–472.

Brown, H. D., McCutcheon, J. E., Cone, J. J., Ragozzino, M. E., & Roitman, M. F. (2011). Primary food reward and reward-predictive stimuli evoke different patterns of phasic dopamine signaling throughout the striatum. *European Journal of Neuroscience*, *34*, 1997–2006.

Chambon, V., & Haggard, P. (2012). Sense of control depends on fluency of action selection, not motor performance. *Cognition*, *125*, 441–451.

Chiviacowsky, S. (2014). Self-controlled practice: Autonomy protects perceptions of competence and enhances motor learning. *Psychology of Sport and Exercise*, *15*, 505–510.

Chiviacowsky, S., & Harter, N. M. (2015). Perceptions of competence and motor learning: Performance criterion resulting in low success experience degrades learning. *Brazilian Journal of Motor Behavior*, *9*(1), 1–10.

Chiviacowsky, S., & Wulf, G. (2007). Feedback after good trials enhances learning. *Research Quarterly for Exercise and Sport*, *78*, 40–47.

Chiviacowsky, S., Wulf, G., & Lewthwaite, R. (2012). Self-controlled learning: The importance of protecting perceptions of competence. *Frontiers in Psychology*, *3*(Article 458). doi:10.3389/fpsyg.2012.00458

Clark, S. E., & Ste-Marie, D. M. (2007). The impact of self-as-a-model interventions on children's self-regulation of learning and swimming performance. *Journal of Sports Sciences*, *25*, 577–586.

Dayan, E., & Cohen, L. G. (2011). Neuroplasticity subserving motor skill learning. *Neuron*, *72*, 443–454.

Deci, E. L., & Ryan, R. M. (2000). The "what" and "why" of goal pursuits: Human needs and the self-determination of behavior. *Psychological Inquiry*, *11*, 227–268.

Deci, E. L., & Ryan, R. M. (2008). Self-Determination theory: A macrotheory of human motivation, development, and health. *Canadian Psychology/Psychologie Canadienne*, *49*, 182–185.

DePasque, S., & Tricomi, E. (2015). Effects of intrinsic motivation on feedback processing during learning. *NeuroImage*, *119*, 175–186.

Eitam, B., Kennedy, P. M., & Higgins, E. T. (2013). Motivation from control. *Experimental Brain Research*, *229*, 475–484.

Ewell, L. A., & Leutgeb, S. (2014). Replay to remember: A boost from dopamine. *Nature Neuroscience*, *17*, 1629–1631.

Friston, K. J. (2011). Functional and effective connectivity: A review. *Brain Connectivity*, *1*, 13–36.

Hartman, J. M. (2007). Self-controlled use of a perceived physical assistance device during a balancing task. *Perceptual and Motor Skills*, *104*, 1005–1016.

Hooyman, A., Wulf, G., & Lewthwaite, R. (2014). Impacts of autonomy-supportive versus controlling instructional language on motor learning. *Human Movement Science*, *36*, 190–198.

Hutchinson, J. C., Sherman, T., Martinovic, N., & Tenenbaum, G. (2008). The effect of manipulated self-efficacy on perceived and sustained effort. *Journal of Applied Sport Psychology*, *20*, 457–472.

Janelle, C. M., Barba, D. A., Frehlich, S. G., Tennant, L. K., & Cauraugh, J. H. (1997). Maximizing performance feedback effectiveness through videotape replay and a self-controlled learning environment. *Research Quarterly for Exercise and Sport*, *68*, 269–279.

Jiao, J., Du, F., He, X., & Zhang, K. (2015). Social comparison modulates reward-driven attentional capture. *Psychonomic Bulletin & Review*, *22*, 1278–1284.

Kal, E. C., van der Kamp, J., & Houdijk, H. (2013). External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Human Movement Science*, *32*, 527–539.

Karsh, N., & Eitam, B. (2015). I control therefore I do: Judgments of agency influence action selection. *Cognition*, *138*, 122–131.

Karsh, N., Eitam, B., Mark, I., & Higgins, E. T. (2016). Bootstrapping agency: How control-relevant information affects motivation. *Journal of Experimental Psychology: General*, *145*, 1333–1350.

Kim, J. H., Han, J. K., Kim, B.-N., & Han, D. H. (2015). Brain networks governing the golf swing in professional golfers. *Journal of Sports Sciences*, *33*, 1980–1987.

Kim, W., Chang, Y., Kim, J., Seo, J., Ryu, K., Lee, E., & Janelle, C. M. (2014). An fMRI study of differences in brain activity among elite, expert, and novice archers at the moment of optimal aiming. *Cognitive And Behavioral Neurology*, *27*, 173–182.

Land, W. M., Frank, C., & Schack, T. (2014). The influence of attentional focus on the development of skill representation in a complex action. *Psychology of Sport and Exercise*, *15*, 30–38.

Lee, W., & Reeve, J. (2013). Self-determined, but not non-self-determined, motivation predicts activations in the anterior insular cortex: An fMRI study of personal agency. *Social Cognitive and Affective Neuroscience*, *8*, 538–545.

Leotti, L. A., & Delgado, M. R. (2011). The inherent reward of choice. *Psychological Science*, *22*, 1310–1318.

Lewthwaite, R., Chiviacowsky, S., Drews, R., & Wulf, G. (2015). Choose to move: The motivational impact of autonomy support on motor learning. *Psychonomic Bulletin & Review*, *22*, 1383–1388.

Lewthwaite, R., & Wulf, G. (2010). Social-comparative feedback affects motor skill learning. *The Quarterly Journal of Experimental Psychology*, *63*, 738–749.

Lewthwaite, R., & Wulf, G. (2012). Motor learning through a motivational lens. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport: Research, theory & practice* (2nd ed., pp. 173–191). London: Routledge.

Locke, E. A., & Latham, G. P. (2006). New directions in goal-setting theory. *Current Directions in Psychological Science*, *15*, 265–268.

Lohse, K. R., Wulf, G., & Lewthwaite, R. (2012). Attentional focus affects movement efficiency. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport: Research, theory & practice* (2nd ed., pp. 40–58). London: Routlegde.

Marchant, D. C. (2011). Attentional focusing instructions and force production. *Frontiers in Psychology*, *1*(Article 210). doi:10.3389/fpsyg.2010.00210

McKay, B., Wulf, G., Lewthwaite, R., & Nordin, A. (2015). The self: Your own worst enemy? A test of the self-invoking trigger hypothesis. *The Quarterly Journal of Experimental Psychology*, *68*, 1910–1919.

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research*, *67*, 22–29.

Menon, V. (2015). Salience network. In A. W. Toga (Ed.), *Brain mapping: An encyclopedic reference* (Vol. 2, pp. 597–611). London: Academic Press, Elsevier.

Murayama, K., Matsumoto, M., Izuma, K., Sugiura, A., Ryan, R. M., Deci, E. L., & Matsumoto, K. (2015). How self-determined choice facilitates performance: A key role of the ventromedial prefrontal cortex. *Cerebral Cortex*, *25*, 1241–1251.

Palmer, K., Chiviacowsky, S., & Wulf, G. (2016). Enhanced expectancies facilitate golf putting. *Psychology of Sport and Exercise*, *22*, 229–232.

Pascua, L. A. M., Wulf, G., & Lewthwaite, R. (2015). Additive benefits of external focus and enhanced performance expectancy for motor learning. *Journal of Sports Sciences*, *33*, 58–66.

Post, P., Fairbrother, J. T., Barros, J. A., & Kulpa, J. D. (2014). Self-Controlled practice with in a fixed time period facilitates the learning of a basketball Set shot. *Journal of Motor Learning and Development*, *2*, 9–15.

Reeve, J., & Tseng, C. M. (2011). Cortisol reactivity to a teacher's motivating style: The biology of being controlled versus supporting autonomy. *Motivation and Emotion*, *35*, 63–74.

Rosenqvist, O., & Skans, O. N. (2015). Confidence enhanced performance? – The causal effects of success on future performance in professional golf tournaments. *Journal of Economic Behavior & Organization*, *117*, 281–295.

Russell, R., Porter, J., & Campbell, O. (2014). An external skill focus is necessary to enhance performance. *Journal of Motor Learning and Development*, *2*, 37–46.

Saddoris, M. P., Sugam, J. A., Cacciapaglia, F., & Carelli, R. M. (2013). Rapid dopamine dynamics in the accumbens core and shell learning and action. *Frontiers in Bioscience (Elite Ed)*, *E5*, 273–288.

Saddoris, M. P., Sugam, J. A., Stuber, G. D., Witten, I. B., Deisseroth, K., & Carelli, R. M. (2015). Mesolimbic dopamine dynamically tracks, and is causally linked to, discrete aspects of value-based decision making. *Biological Psychiatry*, *77*, 903–911.

Saemi, E., Porter, J. M., Ghotbi-Varzaneh, A., Zarghami, M., & Maleki, F. (2012). Knowledge of results after relatively good trials enhances self-efficacy and motor learning. *Psychology of Sport and Exercise*, *13*, 378–382.

Sanli, E. A., Patterson, J. T., Bray, S. R., & Lee, T. D. (2013). Understanding self-controlled motor learning protocols through self-determination theory. *Frontiers in Psychology*, *3* (Article 611). doi:10.3389/fpsyg.2012.00611

Schmidt, L., Braun, E. K., Wager, T. D., & Shohamy, D. (2014). Mind matters: Placebo enhances reward learning in Parkinson's disease. *Nature Neuroscience*, *17*, 1793–1797.

Schmidt, R. A., & Lee, T. D. (2011). *Motor control and learning: A behavioral emphasis* (5th ed.). Champaign, IL: Human Kinetics.

Shafizadeh, M., Platt, G. K., & Bahram, A. (2013). Effects of focus of attention and type of practice on learning and self-efficacy in dart throwing. *Perceptual and Motor Skills*, *117*, 182–192.

Sperduti, M., Delaveau, P., Fossati, P., & Nadel, J. (2011). Different brain structures related to self-and external-agency attribution: A brief review and meta-analysis. *Brain Structure and Function*, *216*, 151–157.

Stoate, I., Wulf, G., & Lewthwaite, R. (2012). Enhanced expectancies improve movement efficiency in runners. *Journal of Sports Sciences*, *30*, 815–823.

Trempe, M., Sabourin, M., & Proteau, L. (2012). Success modulates consolidation of a visuomotor adaptation task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 52–60.

Widmer, M., Ziegler, N., Held, J., Luft, A., & Lutz, K. (2016). Rewarding feedback promotes motor skill consolidation via striatal activity. *Progress in Brain Research*. Published online 7 July 2016. http://dx.doi.org/10.1016/bs.pbr. 2016.05.006

Winstein, C. J., & Schmidt, R. A. (1990). Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 677–691.

Wise, R. A. (2004). Dopamine, learning and motivation. *Nature Reviews Neuroscience*, *5*, 1–12.

Wulf, G. (2007). *Attention and motor skill learning*. Champaign, IL: Human Kinetics.

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *International Review of Sport and Exercise Psychology*, *6*, 77–104.

Wulf, G., Chiviacowsky, S., & Cardozo, P. L. (2014). Additive benefits of autonomy support and enhanced expectancies for motor learning. *Human Movement Science*, *37*, 12–20.

Wulf, G., Chiviacowsky, S., & Drews, R. (2015). External focus and autonomy support: Two important factors in motor learning have additive benefits. *Human Movement Science*, *40*, 176–184.

Wulf, G., Chiviacowsky, S., & Lewthwaite, R. (2012). Altering mindset can enhance motor learning in older adults. *Psychology and Aging*, *27*, 14–21.

Wulf, G., Freitas, H. E., & Tandy, R. D. (2014). Choosing to exercise more: Small choices increase exercise engagement. *Psychology of Sport and Exercise*, *15*, 268–271.

Wulf, G., & Lewthwaite, R. (2010). Effortless motor learning? An external focus of attention enhances movement effectiveness and efficiency. In B. Bruya (Eds.), *Effortless attention: A New perspective in attention and action* (pp. 75–101). Cambridge, MA: MIT Press.

Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-015-0999-9

Wulf, G., McNevin, N. H., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology Section A*, *54*, 1143–1154.

Wulf, G., Raupach, M., & Pfeiffer, F. (2005). Self-controlled observational practice enhances learning. *Research Quarterly for Exercise and Sport*, *76*, 107–111.

Wulf, G., & Toole, T. (1999). Physical assistance devices in complex motor skill learning: Benefits of a self-controlled practice schedule. *Research Quarterly for Exercise and Sport*, *70*, 265–272.

Young, B. B., & Nusslock, R. (2016). Positive mood enhances reward-related neural activity. *Social Cognitive and Affective Neuroscience*, *11*, 934–944.

Zahodne, L. B., Nowinski, C. J., Gershon, R. C., & Manly, J. J. (2015). Self-efficacy buffers the relationship between educational disadvantage and executive functioning. *Journal of the International Neuropsychological Society*, *21*, 297–304.