

SPORTS PERFORMANCE



Autonomy enhances running efficiency

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ABSTRACT

Performer autonomy has been shown to contribute to effective motor performance and learning. Autonomy support is therefore a key factor in the OPTIMAL theory of motor learning (Wulf, G., & Lewthwaite, 2016). The purpose of the present study was to examine whether supporting individuals' need for autonomy by giving them choices would increase movement efficiency. Such a finding would be consistent with the OPTIMAL theory prediction that autonomy facilitates the coupling of goals and actions. Participants ($N = 32$) were asked to run at a submaximal intensity (65% of $\dot{V}O_2 \max$) for 20 minutes. Before the run, participants in a choice group were able to choose 5 of 10 photos as well as the order in which they would be shown to them on a computer screen during the run. Control group participants were shown the same photos, in the same order, chosen by their counterparts in the choice group. Throughout the run, oxygen consumption and heart rate were significantly lower in the choice group than the control group. Thus, providing autonomy support resulted in enhanced running efficiency. The present findings are in line with the notion that autonomy facilitates goal-action coupling.

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Choice; oxygen consumption; heart rate; movement economy

Conditions that support individuals' need for autonomy (e.g. Deci & Ryan, 2000, 2008; Leotti & Delgado, 2011) are vital to well-being and quality of life (e.g. Langer & Rodin, 1976; Ryan & Deci, 2017). Autonomy support is taken here to mean contextual and interpersonal circumstances surrounding task practice that contribute to the performer's feeling of having a say or being in control in his or her actions or behaviors. Autonomy-supportive conditions would include offering control over aspects of practice conditions, providing choices or encouraging expressions of preferences in what is to be performed or how it might be approached. They also include language that conveys some freedom of choice and other opportunities for the performer to derive a sense of agency in task engagement. Autonomy support has also been shown to be important for motivation, performance, and learning (e.g. Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012; Cordova & Lepper, 1996; Tafarodi, Milne, & Smith, 1999; Wulf et al., 2018). Even seemingly inconsequential choices may benefit learning (e.g. Cordova & Lepper, 1996; Tafarodi et al., 1999). Interestingly, incidental choices, or those that are not directly task-relevant, seem to be particularly motivating (Patall, Cooper, & Robinson, 2008).

As numerous studies have demonstrated, the learning of motor skills, including sports skills, is enhanced when learners are given the opportunity to make certain decisions themselves (for a recent review, see Wulf & Lewthwaite, 2016). Since the 1990s, when Janelle and colleagues (Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Janelle, Kim, & Singer, 1995) first demonstrated that learner-controlled (or self-

controlled) feedback facilitated learning of throwing tasks relative to yoked control conditions, many studies have replicated their findings. Aside from learner-controlled feedback (e.g. Aiken, Fairbrother, & Post, 2012; Chiviacowsky & Wulf, 2002, 2005; Chiviacowsky, Wulf, De Medeiros, Kaefer, & Tani, 2008), letting learners determine when to use assistive devices has been shown to be advantageous for learning (Chiviacowsky et al., 2012; Hartman, 2007; Wulf & Toole, 1999). Also, the opportunity to view video demonstrations of a basketball jump shot led to a more effective learning of movement form compared with a yoked group, as measured after a 7-day retention interval (Wulf, Raupach, & Pfeiffer, 2005). Similarly, video feedback enhanced the learning of trampoline skills to a greater extent when it was requested by the learner, as compared with a condition in which learners had no control over the delivery of feedback (Ste-Marie, Verste, Law, & Rymal, 2013). Even choosing the amount of practice can lead to superior learning, as shown in a study by Post, Fairbrother, and Barros (2011). In that study, both movement form and shooting accuracy were enhanced by letting participants decide how many practice shots they wanted to do. On a delayed retention test, the self-control group outperformed a yoked control group. In addition to the learning-enhancing effects of autonomy support, a few recent studies have demonstrated immediate benefits of choice for motor performance (Halperin, Chapman, Martin, Lewthwaite, & Wulf, 2017; Iwatsuki, Abdollahipour, Psotta, Lewthwaite, & Wulf, 2017). In those studies, allowing participants to choose the order of tasks enhanced force production.

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Aside from task-relevant choices (e.g. feedback, assistive devices), even small or incidental choices can benefit motor performance and learning – underscoring the motivational nature of having a choice. For instance, in one study (Lewthwaite, Chiviawsky, Drews, & Wulf, 2015, Experiment 1), providing participants with a small choice, namely, allowing them to choose the color of golf balls (white, orange, or yellow) to be used on a putting task enhanced learning, as measured by a delayed retention test that involved white balls. In a subsequent experiment (Lewthwaite et al., Experiment 2), the learning of the balance task was enhanced by giving learners two choices ostensibly unrelated to the task at hand (i.e. which of two tasks, involving hand grip force or coincidence timing, they wanted to perform after practicing the balance task, and which of two pictures they thought should be hung on the wall). In addition to replicating the effectiveness of task-irrelevant choices, Wulf, Iwatsuki, et al. (2018) demonstrated that task-relevant (video demonstrations of the skill) and task-irrelevant choices (color of mat under target) equally benefited the learning of a lasso-throwing task. In line with these findings, autonomy-supportive instructional language, delivered in a respectful manner (Englert & Bertrams, 2015) or suggesting that learners have some freedom in terms of how they approach task practice, has been found to be more effective than controlling language (Hooyman, Wulf, & Lewthwaite, 2014).

Because of its impact on learning, performer autonomy is one of three key factors in the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016). (The other two factors are enhanced expectancies for future performance and an external focus of attention.) According to the theory, a sense of autonomy allows performers to maintain their attentional focus on the task goal, without the need to engage in self-regulatory activity and suppress negative emotional reactions resulting from controlling environments (e.g. Reeve, Tseng, & Tseng, 2011). Opportunities for choice enhance expectations for positive experience and outcomes, including self-efficacy (Hooyman et al., 2014; Lemos, Wulf, Lewthwaite, & Chiviawsky, 2017; Murayama, Izuma, Aoki, & Matsumoto, 2016). Reward expectations elicit dopaminergic responses that are important for the development of neural connections necessary for successful performance, including the production of force (Foreman et al., 2014). Autonomy is therefore seen as an important contributor to *goal-action coupling* (Wulf & Lewthwaite, 2016). By linking movement goals with necessary actions autonomy leads to effective and efficient motor performance and learning.

While motor learning has consistently been shown to be more effective when practice conditions are autonomy supportive (see above), the notion that movement efficiency should be enhanced when performers have some degree of autonomy still lacks direct empirical support. Indirect evidence comes from two recent studies in which autonomy support led to greater maximum force production (Halperin et al., 2017; Iwatsuki et al., 2017). In the study by Halperin and colleagues, experienced boxers performed a series of different punches under two conditions, a standard condition in which the order of punches was pre-specified and a choice condition in which they selected the order of punches. The choice

condition led to higher punching velocities and greater impact forces. In a subsequent study, Iwatsuki et al. found benefits of choice for a task requiring the production of repeated maximum forces using a hand dynamometer. Participants who were allowed to choose the order of hands on successive trials maintained force levels, whereas a yoked control group showed a significant decline in force across trials.

Maximum force production requires optimal coordination within (e.g. motor unit recruitment) and among muscles (e.g. reduction of unnecessary co-contractions). The studies by Halperin et al. (2017) and Iwatsuki et al. (2017) provide initial indirect evidence that autonomy support may indeed facilitate neurophysiological efficiency – similar to what is seen when performers' expectancies are directly enhanced (Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008; Montes, Wulf, & Navalta, 2018; Stoate, Wulf, & Lewthwaite, 2012) or their attentional focus is directed to the movement goal (e.g. Lohse, Sherwood, & Healy, 2011; Vance, Wulf, Töllner, McNevin, & Mercer, 2004). The purpose of the present study was to examine the effect of autonomy support on motor performance by including direct measures of movement efficiency. Participants were asked to run on a treadmill at a submaximal intensity. The choice given to one group was related to pictures they viewed while running. We used metabolic measures (e.g. oxygen consumption) to test the hypothesis that providing participants with such a relatively small choice would improve running efficiency relative to having no choice (yoked control group).

Methods

Participants

Power analysis software, G*Power 3.1, was used to estimate a required sample size. Based on an estimated large effect size ($f = .57$) with the α -level set at .05 and the power value set at .90, the sample size of 22 participants was needed to detect an effect (Faul, Erdfelder, Lang, & Buchner, 2007). Thirty-two university students volunteered to participate in this study. Their mean age was 22.59 ± 2.46 years (choice: 22.94 ± 2.69 years; control: 22.25 ± 2.24 years). Mean height was 171.10 ± 11.01 cm (choice group: 170.27 ± 10.29 cm; control group: 171.92 ± 11.97 cm), and the average weight was 68.18 ± 15.48 kg (choice group: 71.43 ± 17.33 kg; control group: 66.94 ± 13.57 kg). All participants (16 male, 16 female) had low risk for exercise-related complications (e.g. cardiovascular, pulmonary, metabolic), as determined by the American College of Sports Medicine Risk Stratification Screening Questionnaire. Participants were naïve as to the purpose of the study. They were informed that their fitness level would be assessed. Written informed consent was obtained from all participants before beginning the experiment. The university's institutional review board approved the study.

Apparatus and task

A motor-driven treadmill (T914, Nautilus, Vancouver, WA) was used for walking (warm up) and running. An open-circuit respiratory metabolic system (Moxus, AEI Technologies, Pittsburgh, PA) was calibrated prior to each test and was used to determine

oxygen consumption (VO_2) and respiratory exchange ratio (RER) throughout the two-day experiment. RER indicates how fatty acids and carbohydrate are used. A high RER suggests the predominant use of carbohydrates, whereas a low RER indicates that more fatty acids are being used (Muio, Leddy, Horvath, Awad, & Pendergast, 1994; Pendergast, Leddy, & Venkatraman, 2000). RER is often used as an indicator of exertion, but it is also sensitive to stress (e.g. controlling conditions) (Plowman & Smith, 2017). Given that the stress hormone cortisol has a down-regulatory influence on dopamine (Montoya, Bos, Terburg, Rosenberger, & van Honk, 2014), one might expect to see differences in RER as a function of no-choice versus choice conditions. A heart rate monitor (Polar Electro Inc., Lake Success, NY) was utilized to determine heart rate (HR). The heart rate monitor was positioned on the diaphragm throughout the experiment.

Procedure

Participants were asked to come to the exercise physiology laboratory on two separate occasions. Prior to participating in the experiment on Day 1, participants' height and weight were obtained. All participants then completed a graded exhaustive exercise test to determine their VO_2 max. The initial treadmill speed was set to 3 mph (4.83 km/h) for 2 minutes, followed by 5 mph (8.05 km/h) for 1 minute, and 6 mph (9.66 km/h) for 1 minute. Subsequently, running speed was increased by .5 mph (.08 km/h) every minute until participants reached their self-selected comfortable running speed. That speed was kept throughout the rest of the graded exhaustive test. The grade of the treadmill was then increased by 3 degrees every 2 minutes until the participant could no longer maintain adequate running speed and reached maximum exhaustion. Upon completion of the graded exhaustive exercise test, participants were allowed a cool-down period based on a self-selected pace.

One week later, participants returned to the laboratory and performed a 20-minute submaximal run at a speed that corresponded to 65% of their VO_2 max. Quasi randomization (gender, VO_2 max) was used to assign them to one of the two groups, the choice and control groups. Prior to the run, participants in the choice group were asked to choose 5 of 10 photos shown to them on a computer screen. They were informed that they would be able to see those photos during their run on a monitor placed in front of the treadmill. The photos included 5 city (e.g. New York, Tokyo) and 5 nature motifs (e.g. Yosemite National Park, Rocky Mountains). Participants could also choose the order in which the photo would be displayed. Control group participants were shown the same 10 photos, but were then informed which 5 of those photos they would be seeing during their run, as well as the order in which they would see them. Each participant in the control group was yoked to a participant in the choice group (in terms of the photos and their order), unbeknownst to them. The 5 photos were rotated every minute during the 20-minute run. Thus, each photo was shown 4 times.

Prior to the 20-minute run, participants warmed up for 5 minutes. The warm-up protocol involved an initial walk at 2 mph (3.21 km/h) for 2 minutes, followed by a 3-minute run at 3 mph (4.83 km/h) for 3 minutes. Next, the treadmill was set

to a speed that corresponded to 65% of the participant's VO_2 max, as determined by the metabolic equation in the absence of grade {speed = $[VO_2 \text{ (ml.kg}^{-1}\text{.min}^{-1}) - 3.5]/0.2$ }, provided by the American College of Sports Medicine, & Pescatello, L. S (2014).

Participants ran at that speed for 20 minutes. RER (i.e. ratio between produced carbon dioxide and consumed oxygen), HR , and VO_2 were recorded every 30 seconds. Participants were also asked to rate their perceived exertion every 2 minutes, using Borg's (1982) 20-point rating of perceived exertion (RPE) scale. After the completion of the 20-minute run, participants were given a cool-down period at a self-selected speed. Finally, participants were debriefed about the purpose of the study, provided with feedback (e.g. VO_2 max), and thanked for their time.

Data analysis

RER , HR , and VO_2 data were averaged across 5-minute intervals. RER , HR , and VO_2 data were each analyzed in 2 (group: choice, control) \times 4 (time: 1–5 minutes, 6–10 minutes, 11–15 minutes, 16–20 minutes) repeated-measure analysis of variance (ANOVA). RPE was analyzed in a 2 (group: choice, control) \times 10 (time: every 2 minutes) ANOVA with repeated measures on the last factor. Mauchly's test was used to assess the sphericity assumption. If the assumption was violated, Greenhouse-Geisser epsilon values were used to adjust the degrees of freedom. Bonferroni corrections were used for pairwise post-hoc tests. The level of significance was set to .05.

Results

Maximal exertion measures

On Day 1, all participants performed a VO_2 max test. The results showed no significant differences between the choice and control groups on any measure: VO_2 max (choice: 45.50 ± 7.32 ml.kg $^{-1}$.min $^{-1}$; control: 46.148 ± 6.68 ml.kg $^{-1}$.min $^{-1}$; $p = .661$); RER max (choice: 1.14 ± 0.08 , control: 1.14 ± 0.09 ; $p = .740$); and HR max (choice: 192.80 ± 8.46 , control: 196.07 ± 7.94 ; $p = .536$), $ps > .05$.

Respiratory exchange ratio

RER can be seen in Figure 1. Even though the control group tended to have higher values than the choice group, especially early in the run, the main effect of group, $F(1, 30) = 3.007$, $p = .093$, $\eta_p^2 = .091$, and the interaction of group and time, $F(1.36, 40.71) = 2.466$, $p = .115$, $\eta_p^2 = .076$, were not significant. The main effect of time was significant, $F(1.36, 40.71) = 27.639$, $p > .001$, $\eta_p^2 = .480$.

Oxygen consumption

As can be seen from Figure 2, the choice group had a lower VO_2 than the control group. The main effect of group was significant, $F(1, 30) = 4.408$, $p < .05$, $\eta_p^2 = .128$. The main effect of time was also significant, $F(1.30, 39.08) = 191.072$, $p < .001$, $\eta_p^2 = .864$, reflecting the fact that VO_2 increased for both

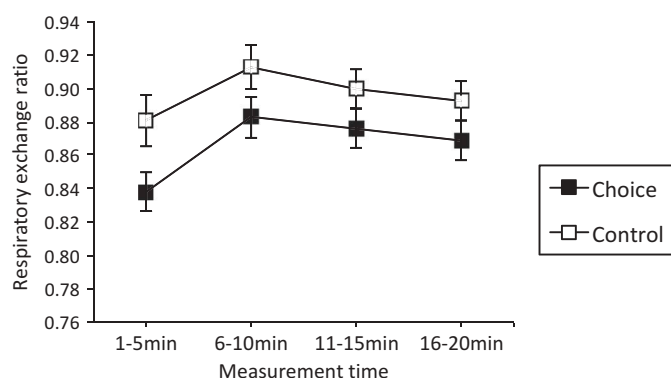


Figure 1. Respiratory exchange ratio (*RER*) in the choice and control group across measurement times.

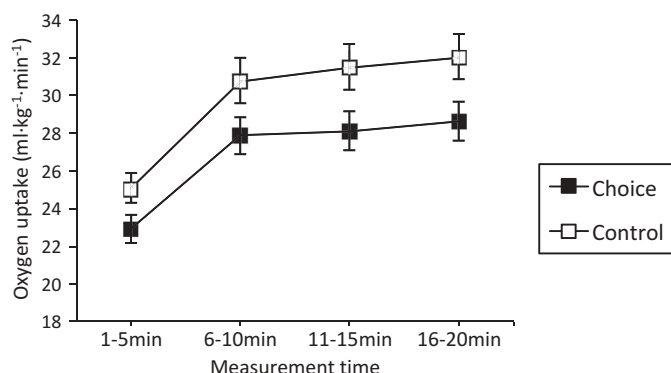


Figure 2. Oxygen uptake (VO_2) in the choice and control groups across measurement times.

groups. The interaction of group and time was not significant, $F(1.30, 39.08) = 1.903$, $p = .174$, $\eta_p^2 = .060$.

Heart rate

Throughout the run, the choice group had lower *HR* than the control group (see Figure 3). The main effect of group was significant, $F(1, 30) = 6.821$, $p < .05$, $\eta_p^2 = .185$. As *HR* generally increased, the main effect of time was also significant, $F(1.37, 41.16) = 198.226$, $p < .001$, $\eta_p^2 = .869$. The interaction of group and time was not significant, $F(1.37, 41.16) = 1.492$, $p = .235$, $\eta_p^2 = .047$.

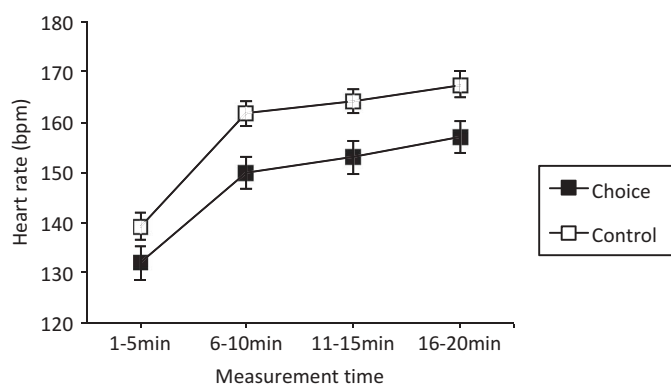


Figure 3. Heart rate (*HR*) in the choice and control group across measurement times.

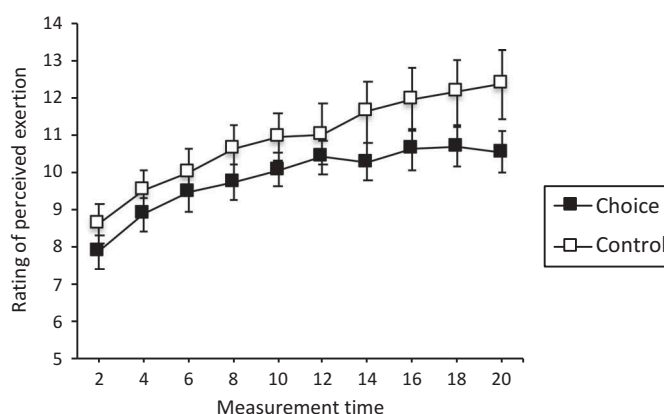


Figure 4. Rating of perceived exertion (*RPE*) reported by the choice and control groups every 2 minutes.

Rating of perceived exertion

RPE generally increased over the 20-minute run (see Figure 4). The main effect of time was significant, $F(1.79, 53.76) = 34.52$, $p < .001$, $\eta_p^2 = .535$. *RPE* did not differ significantly between groups, however, $F(1, 30) = .778$, $p = .385$, $\eta_p^2 = .025$. The interaction of group and time was not significant either, $F(1.79, 53.76) = 1.196$, $p = .307$, $\eta_p^2 = .038$.

Discussion

Running efficiency has been widely examined using various motivational interventions, including injected placebos (saline) (Ross, Grau, & Gill, 2015), altering facial expressions (e.g. smiling) (Brick, McElhinney, & Metcalfe, 2018), self-selected music (Hutchinson et al., 2018), or associative versus dissociative cognitive strategies (for a review, see Masters & Ogles, 1998). The present study examined the effect of autonomy support on running efficiency. The findings are in line with our hypothesis that providing performers with a choice would enhance movement efficiency. Supporting participants' need for autonomy by providing them the opportunity to choose pictures they would view during their submaximal run resulted in reduced oxygen consumption relative to the control group. Oxygen consumption is the product of heart rate, stroke volume, and arteriovenous oxygen difference (Fick equation; Acierno, 2000; Fagard & Conway, 1990). The relationship between oxygen consumption and heart rate has been well documented (e.g. Anderson, 1996; Barnes & Kilding, 2015; Morgan & Craib, 1991; Sparrow & Newell, 1998). In our study, heart rate was also significantly lower in the choice condition. *RER* tended to be reduced in the choice group as well, compared with the no-choice group, although that effect was not statistically significant. Furthermore, subjective ratings of perceived exertion did not differ significantly between groups. Importantly, though, the two main physiological measures (*HR*, VO_2) indicated that the choice group ran more economically than the control group at the same relative speed.

The present findings add an important piece to the mosaic of effects that performer autonomy has on motor performance and learning. They demonstrate that movement efficiency can be enhanced by autonomy-supportive conditions, even if the

choices provided to performers are relatively small and incidental (see Lewthwaite et al., 2015; Wulf, Iwatsuki, et al., 2018). In line with these findings, a study by Lin and Lu (2013, Experiment 2) demonstrated that runners listening to their preferred music showed greater running efficiency, as measured by the distance covered over a 12-minute run. According to the OPTIMAL theory (Wulf & Lewthwaite, 2016), having a sense of autonomy enhances performance and learning in two ways. First, performer autonomy leads to higher expectations for future performance. Autonomy support has indeed been shown to increase perceived competence (Chiviawsky, 2014) or self-efficacy (Chiviawsky, 2014; Hooyman et al., 2014; Wulf, Chiviawsky, & Cardozo, 2014). The positive relationship between self-efficacy (confidence) and motor performance is well documented (e.g. Feltz, Chow, & Hepler, 2008; Moritz, Feltz, Fahrback, & Mack, 2000). In fact, enhancing performance expectancies *directly* has been found to reduce oxygen consumption in experienced runners during a submaximal run (Stoate et al., 2012) and increase maximal oxygen uptake (Montes et al., 2018). Second, autonomy protects the performer from the down-regulatory effect of cortisol on the brain's reward network (Montoya et al., 2014). The stress hormone cortisol is increased under controlling conditions relative to autonomy-supportive conditions (Reeve et al., 2011) and likely degrades performance and learning by reducing dopamine.

Autonomy is a variable that is essential for goal-action coupling, or the fluidity with which the intended movement goal is translated into action (Wulf & Lewthwaite, 2016). An important feature of goal-action coupling is effective and efficient neuromuscular coordination (e.g. recruitment of motor units). Two recent studies have provided preliminary evidence for enhanced neuromuscular coordination by demonstrating benefits of autonomy support for sustained maximum force production (Halperin et al., 2017; Iwatsuki et al., 2017) – an effect that may be due to enhanced excitability of the corticospinal system (i.e. increased amplitudes of motor evoked potentials; Fiorio, Emadi Andani, Marotta, Classen, & Tinazzi, 2014). The need for less oxygen (i.e. greater movement efficiency) seen in the choice condition of the present study also appears to be an indication of enhanced coordination among and/or within muscles. Neural activation patterns typically seen in advanced performers, such as increased efficiency in muscle or motor unit recruitment (e.g. Conley, Stone, Nimmons, & Dudley, 1997; Green & Wilson, 2000; Ploutz, Tesch, Biro, & Dudley, 1994) – and presumably when performance conditions are optimized – are the result of effective connectivity at the central level. Functional connectivity, that is, temporal linkages among task-related neural networks that are seen in expert performers (Bernardi et al., 2013; Kim et al., 2014; Milton, Solodkin, Hlušík, & Small, 2007), is central to the notion of goal-action coupling (see Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016). Choice, or the anticipation of choice, is associated with activity in brain regions that are involved in motivational processes, including the striatum and the ventromedial prefrontal cortex (Murayama et al., 2016). Choice is also associated with dopamine release (Aarts et al., 2012; Lee & Reeve, 2013; Leotti & Delgado, 2011). The assumed mechanisms for autonomy support include its role in generating a dopaminergic response.

Dopamine is thought to contribute to efficient goal-action coupling via functional (and structural) neural connectivity. Reward expectations, such as the anticipation of choice, have been shown to reduce electroencephalographic (EEG) beta activity that inhibits motor activity (Meadows, Gable, Lohse, & Miller, 2016). Dopamine suppresses beta activity (Jenkinson & Brown, 2011) and prepares the motor system for action as seen, for instance, by faster reaction times (Meadows et al., 2016). Dopamine is also involved in cardiovascular regulation and has been shown to be negatively correlated with heart rate (Yeh et al., 2006). Thus, the lower heart rates seen in the choice group may also be a reflection of altered cardiovascular dynamics resulting from a dopaminergic response under autonomy-supportive conditions.

Future studies will likely provide more direct evidence for increased neurophysiological efficiency resulting from autonomy support by examining electromyographic activity or brain activity, including beta suppression, intracortical inhibition (e.g. Kuhn, Keller, Ruffieux, & Taube, 2017), or functional connectivity. It would also be interesting to further explore possible additive effects of autonomy support and other conditions thought to be key to optimal performance (Wulf & Lewthwaite, 2016), such as enhanced expectancies (e.g. Lewthwaite & Wulf, 2010) and an external focus of attention (e.g. Kal, van der Kamp, & Houdijk, 2013). Recent studies have shown that all three factors seem to make unique contributions to performance and learning and have additive effects (Abdollahipour, Palomo Nieto, Psotta, & Wulf, 2017; Chua, Wulf, & Lewthwaite, 2018; Pascua, Wulf, & Lewthwaite, 2015; Wulf et al., 2014; Wulf, Chiviawsky, & Drews, 2015; Wulf, Lewthwaite, Cardozo, & Chiviawsky, 2018). Both enhanced expectancies (Stoate et al., 2012) and an external focus (Schücker, Hagemann, Strauss, & Völker, 2009) have also been shown to improve running economy (i.e. reduce oxygen consumption). Furthermore, all three variables have been found to facilitate sustained force production relative to “neutral” control conditions (Hutchinson et al., 2008; Iwatsuki et al., 2017; Marchant, Greig, Bullough, & Hitchen, 2011). Together these findings show that all factors have the capacity to enhance movement efficiency, in addition to their frequently demonstrated benefits for various measures of movement effectiveness (e.g. accuracy). Whether movement efficiency can be further enhanced by combining autonomy-supportive conditions with those that enhance expectations for performance or promote an external focus remains to be determined.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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