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Maximal force production requires OPTIMAL conditions

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ABSTRACT

The OPTIMAL theory of motor learning identifies several motivational and attentional factors that draw out latent motor performance capabilities. One implication of the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016) is that standardized motor performance assessments likely do not reflect maximal capabilities unless they are "optimized" with appropriate testing conditions. The present study examined the effects of three key motivational (enhanced expectancies, EE, and autonomy support, AS) and attentional (external focus, EF) variables in the OPTIMAL theory on maximum force production. In Experiment 1, a handgrip strength task was used. EE, AS, and EF were implemented, in a counterbalanced order, on consecutive trial blocks in an optimized group. A control group performed all blocks under neutral conditions. While there were no group differences on Block 1 (baseline), the optimized group outperformed the control group on all other blocks. In Experiment 2, participants performed two one-repetition maximum (1-RM) squat lift tests, separated by one week. Two groups, an optimized group and control group, had similar 1-RM values on the first test performed under neutral conditions. However, on the second test, a group performing under optimized conditions (EE, AS, EF) showed an increase in 1-RM, while there was no change from the first to the second test for a control group. We argue that standard test conditions may not produce true maximal performance. The findings corroborate the importance of key factors in the OPTIMAL theory and should be applied to ensure accurate strength performance assessment.

1. Introduction

Numerous standardized tests exist to measure individuals' capabilities thought to be fundamental to motor performance. For instance, tests that are used to assess balance abilities include the BESS test (e.g., Hansen, Cushman, Chen, Bounsanga, & Hung, 2017), MiniBEST test (e.g., Leddy, Crowner, & Earhart, 2011), and Berg Balance Scale (e.g., Major, Fatone, & Ross, 2013). Maximum aerobic capacity is assessed via graded exercise tests (Bruce, Kusumi, & Hosmer, 1973; Poole & Jones, 2017) or sub-maximal testing (Beutner et al., 2015). A variety of tests measure maximum strength such as the isometric mid-thigh pull (e.g., De Witt et al., 2018), vertical jump (e.g., Markovic, Dizdar, Jukic, & Cardinale, 2004), and one-repetition maximum (1-RM) tests (e.g., Levinger et al., 2009). Tests such as these are considered reliable measures of the respective neuromuscular or cardiovascular capacities. However, in recent years it has become increasingly clear that motor performance "cannot be seen anymore as being simply a function of a pure 'motor' system" (Lewthwaite & Wulf, 2010, p. 1). Motor performance can be considered a resultant of many human systems,

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including physiological, biomechanical, social, cognitive, and affective determinants. Indeed, studies have shown that maximum performance can be influenced by variables such as the type and length of warm-up (Abad, Prado, Ugrinowitsch, Tricoli, & Barroso, 2011), caffeine intake (Grgic, Trexler, Lazinica, & Pedisic, 2018), self-selected music (van den Elzen et al., 2019), and anger or happiness (Rathschlag & Memmert, 2013).

Here, we focus on brief instructional interventions, aimed at enhancing performers' motivation and attentional focus, that have the potential to draw out latent motor performance capabilities. For example, maximal aerobic capacity has been shown to be higher after positive feedback (Montes, Wulf, & Navalta, 2018). Maximum muscular force production is a function of the performer's focus of attention (e.g., Halperin, Chapman, Martin, & Abbiss, 2017). Also, balance performance (and learning) have been shown to be enhanced by external attentional focus instructions (e.g., Jackson & Holmes, 2011) or conditions that involve choices (e.g., Chiviacowsky, Wulf, Lewthwaite, & Campos, 2012). Thus, the findings of those studies cast doubt on the idea that standardized tests, with "neutral" test instructions, actually measure maximum or optimal performance.

The findings are consistent with the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016), though, according to which optimal performance conditions require the presence of three variables: Enhanced expectancies (EE) for future performance, autonomy support (AS), and an external focus (EF) of attention. These factors are considered key to both optimal (or maximal) performance and learning. Even small differences in the wording of task instructions can impact performers' attentional focus or motivational states and can immediately alter motor performance (for reviews, see Lewthwaite & Wulf, 2017; Wulf & Lewthwaite, 2016). Instructions or other conditions that boost performers' expectancies, support their need for autonomy, or promote an external focus have each been found to result in more effective performance relative to conditions in which performers are deprived of those factors (e.g., given negative feedback or internal focus instructions). Importantly, they have also been shown to be more effective than presumably neutral control conditions such as those encountered in typical test situations.

Performers' expectancies can be enhanced, for example, through the provision of positive feedback. Studies have shown that such feedback enhanced running efficiency (Stoate, Wulf, & Lewthwaite, 2012) or sustained force production (Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008) compared with control conditions (for an exception, see Halperin, Chapman, Thompson, & Abbiss, 2019). Conditions that are supportive of performers' need for autonomy (e.g., by providing choices) can also enhance motor performance. Allowing kickboxers to select the order of different punches resulted in greater impact forces and punching velocities than did a control condition with a predetermined order (Halperin, Chapman, Martin, Lewthwaite, & Wulf, 2017). Another study by Lemos, Wulf, Lewthwaite, and Chiviacowsky (2017) showed that maximum forces were sustained across repetitions in an autonomy-supportive condition, whereas a decline was seen in a control group, suggesting that the efficiency of muscle contractions (e.g., motor unit recruitment) might be enhanced by AS. More direct evidence for increased movement efficiency comes from studies showing greater running economy under AS relative to control conditions (Iwatsuki, Navalta, & Wulf, 2019) or reduced muscular activity in force production tasks (Iwatsuki, Shih, Abdollahipour, & Wulf, 2019). Finally, the importance of adopting an external focus on the intended movement effect has been demonstrated in numerous studies (for a review, see Wulf, 2013). Performance advantages resulting from an EF, relative to control conditions, have been found for balance performance (e.g., Wulf, Landers, Lewthwaite, & Töllner, 2009, maximum force production (e.g., Abdollahipour, Psotta, & Land, 2016; Halperin, Williams, Martin, & Chapman, 2016; Hansen et al., 2017; Wulf & Dufek, 2009), movement speed (Porter, Nolan, Ostrowski, & Wulf, 2010; Porter, Wu, Crossley, Knopp, & Campbell, 2015) and many other tasks.

In addition to each factor (EE, AS, EF) individually benefiting performance (and learning) relative to control conditions, a recent series of studies has shown that these factors can have additive benefits. Conditions that included combinations of two factors resulted in greater benefits for performance (Abdollahipour, Palomo Nieto, Psotta, & Wulf, 2017; Marchant, Carnegie, Wood, & Ellison, 2019) or learning (Pascua, Wulf, & Lewthwaite, 2015; Wulf, Chiviacowsky, & Cardozo, 2014; Wulf, Chiviacowsky, & Drews, 2015) than did those that included only one of these factors, or none. Moreover, the presence of all three factors enhanced learning to an even greater extent than did combinations of two factors (Wulf, Lewthwaite, Cardozo, & Chiviacowsky, 2018). Two recent studies addressed the question whether motor performance could be immediately enhanced by implementing all three factors in succession (Abdollahipour, Valtr, & Wulf, 2020; Chua, Wulf, & Lewthwaite, 2018). Abdollahipour et al. (2020) found that children's bowling performance was enhanced by each variable. After a baseline test, a so-called OPTIMAL group was provided EE, AS, and EF on three consecutive trials blocks, in a counter-balanced order. Relative to a control group that performed all blocks under neutral conditions, the OPTIMAL group demonstrated greater bowling accuracy (more pins knocked down) on all three blocks. Utilizing a similar design to measure maximum vertical jump performance, Chua et al. (2018) found greater jump height on blocks on which the so-called optimized group received one of the three variables. Moreover, with each addition of a variable on successive blocks of trials, jump height increased further whereas it did not change in a control group.

Given the importance of these findings from both theoretical and practical perspectives – including maximal performance testing – the present study sought to replicate and extend the recent findings (Abdollahiour et al., 2020; Chua et al., 2018). Specifically, the study asked whether maximum force production could be enhanced by "optimized" conditions that include EE, AS, and EF relative to control conditions. Two experiments were conducted to examine this question. In the first experiment, maximum handgrip strength was measured, and the three factors were implemented in succession in one group (optimized). In Experiment 2, a 1-RM free squat lift task was used and all three factors were applied at the same time in an optimized condition. It was hypothesized that maximum force production (grip strength, weight lifted) would be increased relative to control conditions.

2. Experiment 1

In the first experiment, measured maximum grip strength was measured with a hand-held dynamometer. Handgrip strength is often used in clinical settings and is seen as a predictor of general muscular strength and endurance (e.g., Trosclair et al., 2011). It was hypothesized that an “optimized” condition that included EE, AS, and EF would result in greater maximum handgrip forces relative to a “neutral” control condition.

2.1. Method

2.1.1. Participants

Forty-eight university students (28 females, 20 males, mean age = 22.4 ± 4.09), recruited from a university convenience sample, participated in the present study. Participants were enrolled in a motor control and learning course, but data were collected before any material relevant to the present study was discussed in class. All participants were naïve to the specific purpose of the experiment. Participants signed an informed consent form before participating in the experiment, which was approved by the university's institutional review board.

2.1.2. Apparatus and task

Grip strength was measured using a handgrip dynamometer (Hoggan Scientific, Salt Lake City, Utah). Each participant was seated in a straight-back chair with no armrests. The dynamometer was held in a handshake position with the elbow flexed at a right angle by the side of the body. The display of the dynamometer was facing away from the participants and toward the experimenter, so that participants did not receive feedback about the forces they produced.

2.1.3. Procedure

Participants were quasi-randomly assigned to one of two groups, the optimized and control groups, with an equal number of males and females in each group. Participants were instructed on how to properly grasp the dynamometer, including elbow flexion and facing of the display screen. They were then asked to perform two maximum effort trials with each hand in the order of dominant, non-dominant, dominant, and non-dominant. This first block of four trials was considered the baseline assessment. Subsequently, all participants performed three additional blocks of four trials using the same order of hands, with the exception of one block (see below). Instructions on those three blocks varied depending on the group to which participants had been assigned. In the optimized group, participants performed the three blocks under EE, AS, or EF conditions in a counterbalanced order. In the EE condition, participants were given false social-comparative feedback indicating that the forces they produced on the previous four trials were better than average for their age and gender. In the AS condition, participants were free to choose the order of hands, with the restriction that each hand be used twice. Participants in the control group were yoked to an experimental counterpart of same sex with respect to hand order in the respective trial block. In the EF condition, optimized group participants were asked to concentrate on the dynamometer. No other instructions were given. At the conclusion of the study, participants were debriefed about the study purpose and false feedback.

2.1.4. Data analysis

Maximum forces in each block were averaged across the four trials from both hands. To account for possible group differences in baseline performance (Block 1), changes in maximum force for each block relative to Block 1 were determined (similar to Chua et al., 2018). These relative changes in force were analyzed with a 2 (groups: optimized, control) x 3 (conditions: EE, AS, EF) mixed-factor analysis of variance (ANOVA) with repeated measures on the second factor. In addition, we wanted to determine whether the addition of a variable (e.g., EF then AS then EE) would result in increases in maximum force production. Therefore, maximum forces were compared with a 2 (groups: optimized, control) x 4 (blocks) ANOVA that included a chronological order of all blocks. Effect sizes are reported as partial eta squared values. Statistical analyses were performed with $p < .05$ as the criterion for statistical significance.

2.2. Results

The optimized ($M = 32.77$ kg, $SD = 11.68$) and control ($M = 32.32$ kg, $SD = 10.17$) groups did not differ significantly on the first block, F (1, 46) < 1. However, maximum forces differed between groups on the subsequent blocks. Fig. 1 shows changes in maximum forces relative to baseline (Block 1) for the optimized and control groups. When AS, EE, or EF were introduced in the optimized group, forces were significantly higher relative to the control group. As shown in Fig. 1, all three conditions in the optimized group enhanced performance. The main effect of group was significant, $F\,(1, 46) = 10.24$, $p = .002$, $\eta_p^2 = 0.182$. There was no significant main effect of condition, $F\,(2, 92) < 1$, or interaction of group and condition, $F\,(2, 92) < 1$.

Fig. 2 shows maximum forces across Blocks 1–4. Participants in the optimized group demonstrated an increase in forces relative to baseline (Block 1), whereas no such increase was seen for the control group. The interaction of group and block was significant, $F\,(3, 138) = 4.60$, $p = .004$, $\eta_p^2 = 0.091$. Follow-up ANOVAs within each group showed a significant effect of block for the optimized group, $F\,(3, 69) = 3.45$, $p = .021$, $\eta_p^2 = 0.130$, but not for the control group, $F\,(3, 69) = 1.89$, $p = .139$, $\eta_p^2 = 0.076$. Pairwise comparisons indicated that Blocks 3 and 4 differed from Block 1 in the optimized group, $p < .05$. The main effects of block, $F\,(3, 138) = 1.17$, $p = .323$, $\eta_p^2 = 0.025$, and group, $F\,(1, 46) < 1$, were not significant.

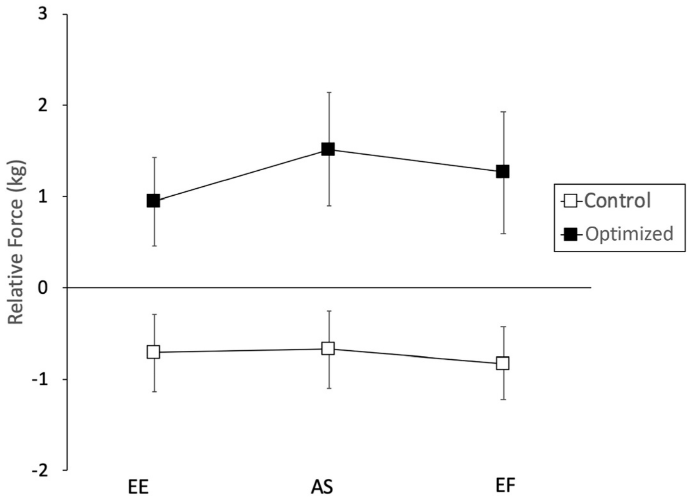

Fig. 1. Changes in force relative to baseline for the optimized (EE, AS, EF conditions) and control groups. Error bars represent standard errors.

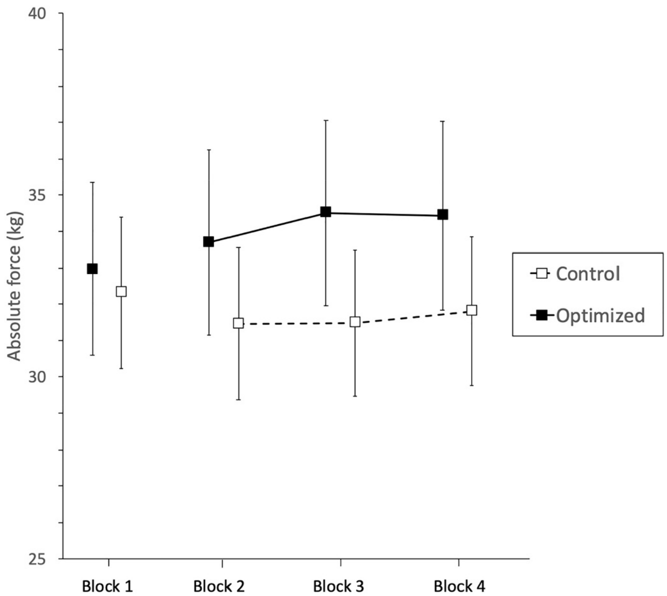

Fig. 2. Maximum force across blocks for the optimized and control groups. Error bars represent standard errors.

2.3. Discussion

Handgrip strength measurements have been widely used in investigations assessing its value as a field-testing measure (Ruiz et al., 2011) or prognostic tool in clinical settings with people over the age of 60 (Rijk, Roos, Deckx, van den Akker, & Buntinx, 2016). While some physiological factors (e.g., Abad et al., 2011; Grgic et al., 2018) have been shown to influence maximum performance, the purpose of the present experiment was to determine if key factors (EE, AS, EF) in the OPTIMAL theory (Wulf & Lewthwaite, 2016), when introduced in succession, would produce greater benefits compared with neutral task instructions in a standardized handgrip strength assessment. Participants were tasked with repeated attempts to produce maximal force with their dominant and non-dominant hands. The results of the present study indicate that the control condition did not elicit the true maximum grip forces. Rather, introducing EE, AS, and EF, in any order, improved handgrip strength performance.

Moreover, cumulative effects of all three factors led to a significant increase in maximum forces over time in the optimized group, in contrast to the control group whose performance did not change. Those findings are in line with those of Chua et al. (2018) who found incremental benefits of the three factors for maximum jump height. Similar to Chua et al., EE, AS, or EF were successively added in the same group of performers (optimized group). That is, conditions from previous blocks were not repeated. However, it appears that participants either remembered them, or that the conditions had a sufficiently lasting effect. This suggests that the three factors make at least partially independent contributions to enhanced performance (or learning) (e.g., Abdollahipour et al., 2017;

Chua et al., 2018; Lemos et al., 2017; Pascua et al., 2015). It is possible that different dopaminergic responses to motivational influences such as EE or AS and/or more efficient goal-action coupling with an EF (e.g., Kuhn, Keller, Lauber, & Taube, 2018; Kuhn, Keller, Ruffieux, & Taube, 2017; Meadows, Gable, Lohse, & Miller, 2016) exert their influences when all three variables are applied. The exact nature of these mechanisms will need to be investigated in future studies.

3. Experiment 2

Given the potential importance of the findings of Experiment 1 for maximum performance testing, we conducted a second experiment to determine the generalizability of our results. A task with a greater number of degrees of freedom, a 1-RM free squat lift, was used in Experiment 2. Furthermore, rather than implementing the three OPTIMAL theory (Wulf & Lewthwaite, 2016) key factors (EE, AS, EF) in succession, they were applied at the same time in an optimized condition. Two groups of participants with weighlifting experience first performed a baseline test (Test 1) and one week later another test (Test 2) under either control or optimized conditions. It was hypothesized that the optimized group would show an increase in 1-RM on Test 2 relative to Test 1, whereas the control group would show no increase.

3.1. Method

3.1.1. Participants

Thirty-two participants from a university student population participated in the study. All participants were healthy and free from any conditions that would limit participation in maximal squat strength testing. Their mean age was 23.9 ± 2.85 years. All participants had a minimum of six months resistance training experience prior to study completion and were actively performing strength training exercises on a regular basis each week. Most participants had not taken a motor control and learning class, while others who were enrolled in that class had not yet been taught any material relevant to the present study. Participants were not informed about the specific purpose of the experiment. They signed an informed consent form before participating in the experiment. The study was approved by the university's institutional review board.

3.1.2. Apparatus and task

Participants were asked to perform attempts at a 1-RM free-weight back squat. A 1-RM was defined as the greatest resistance load under which a participant could successfully perform a weighted back squat. The back squat task was performed in a controlled laboratory setting, utilizing a 45-lbs (20.41 kg) barbell, weight plates (5, 10, 25, 35, and 45 lbs), and a squat rack. Proper safety spotting procedures were followed for all participants. Spotting was done by the experimenter and assistants from behind the participant and at both ends of the barbell. Specific shoes were not required; however, all participants were instructed to wear the same shoes on both testing days in order to avoid any potential effects on performance.

3.1.3. Procedure

Participants were quasi-randomly assigned to one of two groups, with an equal number of males and females, and with similar 1-RM values in each group. Sixteen participants (8 females, 8 males, mean age = 23.9 ± 2.7 years; resistance training experience = 6.7 ± 4.2 years) completed the squat protocol in the optimized group, while sixteen participants (8 females, 8 males, mean age = 23.9 ± 3.0 years; resistance training experience = 6.5 ± 3.8 years) served in the control group. Eighty-eight percent of control group and 94% of optimized group participants had performed a 1-RM squat lift before. All participants were asked to complete two experimental testing sessions. Participants were instructed not to participate in resistance training of the lower extremities for at least two days (48 h) prior to each session.

In the first test session, participants performed 1-RM testing to establish baseline squat performance under the same conditions. They were first provided with a demonstration of proper squat form by the experimenter (see Haff & Triplett, 2016). Prior to a standardized warm-up protocol for the 1-RM test, all participants were asked to estimate their 1-RM based on previous experience. This estimated 1-RM value was used to determine load percentages for the warm-up sets. During warm-up and exercise sets, no feedback was given with regard to form unless it was deemed necessary for the safety of the participant. The warm-up protocol began by participants walking for three minutes at 3–6 miles per hour on a treadmill, followed by 15 squat repetitions with a 45-lbs barbell. A one-minute rest period was provided. In the next warm-up set, participants performed eight repetitions at 50% of their estimated 1-RM. A one-minute rest period was provided. Following this rest period, participants were instructed to perform four repetitions at 70% of their estimated 1-RM followed by a two-minute rest period. Finally, participants were instructed to perform two repetitions at 90% of their estimated 1-RM followed by a three-minute rest period. Upon the conclusion of the warm-up, resistance load was increased to the estimated 1-RM load. Participants were instructed to perform a maximal effort attempt that was recorded as their first 1-RM attempt. Upon completion of a successful 1-RM attempt, resistance load was increased by 10 lbs. (4.54 kg). If that attempt failed, the resistance load was reduced by 5 lbs. (2.27 kg) and participants were asked to complete another attempt. Resistance load continued to be increased or decreased until the participant could complete one repetition with proper technique. All participants were permitted three to five testing sets in order to attain a 1-RM (see Haff & Triplett, 2016). Three-minute rest periods were provided between 1-RM attempts. The 1-RM was deemed to be reached based upon two criteria: 1) the participant was unable to successfully perform the repetition, or 2) the participant verbally expressed that he/she did not believe they would be able to perform a subsequent successful 1-RM lift. To ensure participant safety, the total number of 1-RM attempts was solely based on participant feedback (Hoffman, 2012).

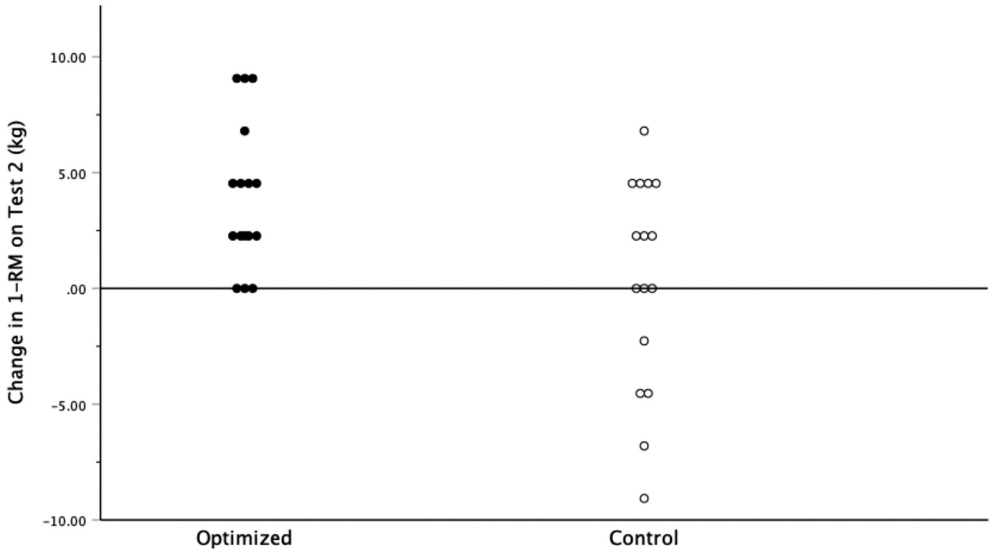

Fig. 3. Maximum weight lifted (1-RM) on Test 2, relative to Test 1, in optimized and control groups shown for individual participants (each dot represents one participant).

Test 2 was conducted one week later to minimize any potential effects of physiological adaptations and to ensure adequate recovery. During the second session, participants performed a 1-RM test under one of two conditions, control or optimized. In the optimized group, participants were given positive feedback (EE) two times during the three warm-up sets, and after each maximal effort attempt (e.g., "nice job," "you did well", "your form looked great"). AS was provided by allowing participants to choose the amount of weight to increase or decrease after each maximal effort attempt (0–10%). An EF was implemented by instructing participants to concentrate on the movement path of the barbell during the squat lift. Reminders of this EF were given before each warm-up set and before each maximal effort attempt. In the control group, participants followed the protocol utilized during the baseline 1-RM testing (Test 1). However, they were yoked to the participants in the optimized condition with regard to percentage of resistance load increase or decrease between maximal effort attempts. For example, if a participant in the optimized group chose to increase resistance load by 10% (AS) from one attempt to the next, the participant yoked to his or her gender-matched counterpart was instructed to increase resistance load by 10% as well during the same maximal effort attempt.

3.1.4. Data analysis

Average maximum weights lifted, or 1-RM, on Tests 1 and 2 were compared in a 2 (group: optimized, control) x 2 (test) ANOVA with repeated measures on the last factor. Effect sizes are reported as partial eta squared values.

3.2. Results

The control (108.3 kg) and optimized (106.6 kg) groups had similar average 1-RM values on Test 1 (baseline). On Test 2, one week later, the control group showed only a slight average increase of 0.283 kg (108.6 kg total), whereas the optimized group demonstrated a substantially greater increase of 4.0 kg (110.6 kg total). Fig. 3 shows, for individual participants, their change in 1-RM on Test 2, relative to Test 1. The average change in 1-RM performance corresponded to 0.57% and 4.12% for the control and optimized groups, respectively. A significant Group x Test interaction, $F\,(1,30) = 6.98$, $p = .013$, $\eta^2 = 0.24$, confirmed the groups' differential improvement. Follow-up ANOVAs revealed that participants in the control group demonstrated no significant increase, $F\,(1, 15) = 0.61$, $p = .809$, $\eta^2 = 0.004$, whereas the optimized group did show significantly higher 1-RM values on Test 2 relative to Test 1, $F\,(1, 15) = 25.35$, $p < .001$, $\eta^2 = 0.63$. Due to the optimized group's 1-RM increase from Test 1 to 2, the main effect of test was also significant, $F\,(1, 30) = 9.30$, $p = .005$, $\eta^2 = 0.24$. There was no significant main effect of group, $F\,(1, 30) < 1$.

3.3. Discussion

One-repetition maximum tests can potentially be influenced by an (unconscious) bias of the person(s) administering the test. Biases may be based on expectations related to the gender, age, or other characteristics of the person performing the test (e.g., Barbalho et al., 2018), or expectations of the effectiveness of certain performance conditions. In the present study, we attempted to eliminate the possibility of experimenter bias by leaving the decision of when the maximum was reached up to the participant. Ideally, tests such as the 1RM test should be administered by blinded testers.

One-repetition maximum tests, including the squat lift, are typically considered reliable measures of muscular strength (e.g., Seo et al., 2012). However, in the present experiment, 1-RM free squat lift performance showed a significant increase when participants performed in a condition that included factors considered key to "optimal" performance (EE, AS, EF). Relative to baseline performance measured under neutral conditions (Test 1), performers in the optimized group showed an increase of more than 4% in the maximum weight they were able to lift. If this improvement had been due to practice or familiarization with test procedures, a similar increase would have been seen in the control group. However, this was not the case. The control group showed no significant difference in Test 1 and Test 2 performances (see also Seo et al., 2012). Thus, a testing protocol that enhanced performers' expectancies (EE) by including positive feedback, provided them with (small) choices (AS), and incorporated EF instructions by directing their attention to the barbell resulted in greater "maximum" performance.

The purpose of this study was not to tease out mechanisms described in the OPTIMAL theory (2016) or examine how much each of the three factors contributed to the observed effect. Rather, we primarily wanted to examine implications of the theory and to extend the notion of "optimized" performance to standardized applied testing (see also Chua, Wulf, & Lewthwaite, 2020). We implemented all three factors – all of which, individually, have been shown to result in benefits for performance, including force production (e.g., Hansen et al., 2017; Hutchinson et al., 2008; Iwatsuki, Abdollahipour, Psotta, Lewthwaite, & Wulf, 2017) – simply because it provided an arguably stronger test of "optimization" conditions relative to conventional control conditions. Overall, the present findings replicated those of Experiment 1 by showing that maximum or optimal performance is a function of the conditions under which it is measured.

4. General discussion

Why do supposedly neutral test conditions not result in optimal performance? Conditions that, in one way or another, promote a focus on the self or other task-unrelated thoughts tend to produce less-than-maximum performance (Wulf & Lewthwaite, 2010, 2016). Typical test situations arguably contain a number of self-invoking triggers (e.g., McKay, Wulf, Lewthwaite, & Nordin, 2015). These triggers may include the presence of others, measurement devices, suggestions of fixed abilities, instructions delivered in a directive manner or controlling language, expectations of maximum effort, or task instructions related to body movements resulting in an internal focus of attention (see McKay et al., 2015; Wulf, 2013; Wulf & Lewthwaite, 2016). Self-referential thoughts, which are related to activation of the brain's default mode that also facilitates mind wandering (e.g., Buckner, Andrews-Hanna, & Schacter, 2008), interfere with effective task performance. Optimal performance requires functional connectivity of task-related neural motor networks (e.g., Di & Biswal, 2015), or goal-action coupling (Wulf & Lewthwaite, 2016). The efficient coupling of goals and actions is facilitated by conditions that allow the performer to direct attention to the task while at the same time reducing a detrimental self-focus.

The latter conditions are met when EE, AS, and EF are present. Performance conditions that involve EE are assumed to promote a focus on the task goal and to suppress self-related thoughts (see Wulf & Lewthwaite, 2016). They trigger dopaminergic responses that facilitate functional connectivity (Wise, 2004). AS conditions also enable performers to maintain their focus on the task goal by enhancing performer confidence or self-efficacy (e.g., Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017), without the need to engage in self-regulatory activity. Moreover, they promote positive affect in contrast to the negative emotions resulting from controlling environments (e.g., Hooyman, Wulf, & Lewthwaite, 2014; Reeve & Tseng, 2011). Finally, the benefits of adopting an external focus on the intended movement effect or task goal have been demonstrated in numerous studies (Wulf, 2013). By preventing a detrimental internal (or self) focus, it is assumed to directly promote functional connectivity for task performance (Kuhn et al., 2017).

Overall, the present findings corroborate the importance of the key variables in the OPTIMAL theory (Wulf & Lewthwaite, 2016) for optimal motor performance. There is converging evidence that supposedly neutral control conditions are not conducive to truly maximal performance. While individual key variables (EE, AS, or EF) have been shown to enhance performance, including maximum force production (e.g., Iwatsuki et al., 2017) or aerobic capacity (Montes et al., 2018), the presence of all three factors seems to be necessary for optimal motor learning (Wulf et al., 2018). Moreover, there is evidence for incremental performance enhancements with the addition of more factors (Abdollahipour et al., 2017; Chua et al., 2018; Marchant et al., 2019. Aside from providing support for OPTIMAL theory predictions, the findings have implications for performance testing in applied settings. Using optimal performance conditions can help testers ensure that their measurements for a maximum neuromuscular or cardiovascular assessment are as close as possible to maximal performance when that is the desired outcome. While false social-comparative information ("you are performing better than the average"), such as that used in Experiment 1, is not recommended for practical settings due to its deceptive nature, positive feedback (Experiment 2), simple encouraging comments (e.g., Wulf, Chiviacowsky, & Lewthwaite, 2012), or liberal definitions of success (Palmer, Chiviacowsky, & Wulf, 2016; Ziv, Ochayon, & Lidor, 2019) can serve as a means for enhancing expectancies. Furthermore, small or even incidental choices (Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015), or non-controlling instructional language that implies opportunities for choice (Hooyman et al., 2014), can support performers' need for autonomy. Finally, instructions that direct performers' attention externally, or to the intended movement effect, are important although the optimal external focus can vary depending on the task goal and perhaps level of expertise (see Wulf, 2013). The notion that motor performance is "pure" and independent of social-cognitive-affective influences has outlived its usefulness (Lewthwaite & Wulf, 2010). Practitioners and researchers alike need to be aware of these influences in their work with athletes, patients, or study participants.

Standard tests are assumed to objectively and reliably measure people's physical or coordinative capabilities. Yet, the present study shows that "neutral" test conditions may not be able to elicit maximum or optimal performance. Rather, motor performance is optimized when test conditions enhance individuals' expectancies for performance, include choices to support their need for autonomy, and promote an external focus of attention. Performing under these conditions aligns performers' thoughts, motivation, attention, and neuromuscular systems to their action goals (goal-action coupling; Wulf & Lewthwaite, 2016). These findings have important implications for practitioners and scientists interested in creating conditions for optimal performance.

Declarations of Competing Interest

None.

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