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BRIEF REPORT

Limiting motor skill knowledge via incidental training protects against choking under pressure

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Abstract

The paradoxical harmful effects of motivation and incentives on skilled performance ("choking under pressure") are observed in a wide variety of motor tasks. Two theories of this phenomenon suggest that choking under pressure occurs due to maladaptive attention and top-down control, either through distraction away from the task or interference via an overreliance on controlled processing of a skilled task. A third theory, overmotivation (or overarousal), suggests that under pressure, "instinctive" or Pavlovian approach/withdrawal responses compete with the desired response. Only the two former theories predict that choking under pressure would be less likely to occur if an individual is unaware of the skill over which to assert top-down control. Here we show that only participants who train and perform with premovement cues that allowed for preparatory movement planning choke under pressure due to large monetary incentives, and that this effect is independent of the level of skill attained. We provide evidence that this might be due to increased movement variability under performance pressure. In contrast, participants trained incidentally to reduce explicit skill knowledge do not modulate performance on the basis of incentives and appear immune to choking. These results are most consistent with distraction theories of choking and suggest that training strategies that limit awareness may lead to skills that are more robust under performance pressure.

Keywords Cognitive control and automaticity · Implicit vs. explicit memory · Attention and executive control · Skill acquisition

In Game 1 of the 1995 NBA finals, Nick Anderson of the Magic, a career 70% free-throw shooter, was fouled and given two free throws with his team up three points and only 10 s left. A single make would put the game out of reach. After badly missing both shots, the ball miraculously bounced back into his hands, and he was immediately fouled again . . . and again missed both free throws. On the basis of his shooting percentage, this turn of events was incredibly unlikely (<1% chance of four straight misses). After his team went on to lose the game, sports commentators immediately declared that Anderson had clearly "choked under pressure."

Choking describes instances wherein the execution of a skill fails under high levels of pressure, when the desire for superior performance is maximal but leads to poorer outcomes than would otherwise be expected (Baumeister, 1984; Baumeister & Showers, 1986). In controlled laboratory environments, impaired performance under pressure has been induced on a wide range of sensorimotor tasks (Baumeister, 1984; Beilock & Carr, 2001; Chib, De Martino, Shimojo, & O'Doherty, 2012; Lee & Grafton, 2015; Mobbs et al., 2009).

Two psychological theories of this phenomenon—*distraction* and *explicit monitoring*—both suggest that, following an appraisal of performance pressure, a shift in attention and executive control is responsible for the collapse in performance.

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This shift is either away from necessary task control onto irrelevant internal factors such as worries about failure (Beilock, Bertenthal, McCoy, & Carr, 2004; Beilock & Carr, 2005; Eysenck, Derakshan, Santos, & Calvo, 2007) or onto the execution of the individual steps of a cognitive or motor operation, adversely influencing smooth, procedural performance (Beilock & Carr, 2001; Kimble & Perlmuter, 1970; Lewis & Linder, 1997; Masters, 1992). A separate class of theories, favored by behavioral economists and some cognitive neuroscientists, argue that *overmotivation* (sometimes called *overarousal*) leads to increased arousal (Ariely, Gneezy, Loewenstein, & Mazar, 2009; Mobbs et al., 2009; Yerkes & Dodson, 1908). A very high level of motivation/arousal is thought to disrupt motor performance, perhaps through the triggering of aversive Pavlovian withdrawal responses in the face of a potentially large loss (Chib et al., 2012; Chib, Shimojo, & Doherty, 2014). A better understanding of which of these mechanisms lead to choking in a specific context can provide insight into motivation–cognition interactions but could also aid in the design of training strategies to mitigate the negative effects of performance pressure.

Certain motor-sequencing skills are thought to be under the purview of dual processes/controllers (Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013; Logan & Crump, 2011; Willingham, Salidis, & Gabrieli, 2002)—one top-down and strategic (e.g., "cognitive," "explicit," etc.) and the other bottom-up and automatic (e.g., "procedural," "implicit," etc.). Both the distraction and explicit-monitoring theories appeal to this duality in control and require that an individual be capable of exerting top-down control over skilled performance. However, these skills can be trained and performed with a limited role for top-down control, either by training incidentally outside of awareness (Reber & Squire, 1994; Willingham, 1998) or by engaging cognitive control resources with a secondary task (Curran & Keele, 1993; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). When participants are explicitly told and/or cued to existence of repeating sequences, learning is dependent on working memory (WM) and is associated with increased activity in the prefrontal cortex, which is known to be important for top-down control (Janacsek & Nemeth, 2013). In contrast, incidental sequence learning does not depend on WM and, in fact, can occur when a demanding secondary task is used to occupy WM resources (e.g., Foerde, Knowlton, & Poldrack, 2006). In fact, promoting implicit skill-learning strategies has been previously shown to reduce the negative impact of a distracting secondary task (Maxwell, Masters, Kerr, & Weedon, 2001). In addition, many functional brain-imaging studies have demonstrated the dissociability of underlying brain networks during the implicit versus explicit acquisition (Grafton, Hazeltine, & Ivry, 1995, 1998; Hazeltine, Grafton, & Ivry, 1997) and retrieval (Bischoff-Grethe, Goedert, Willingham, & Grafton, 2004) of motor skills.

Proponents of both distraction and monitoring might predict that restricting the role of top-down control in skill acquisition and performance by limiting skill awareness could lead to reduced susceptibility to choking. If a skill is learned incidentally, successful performance would not rely on executive control resources such as WM, and occupying WM with distracting thoughts about failure (as a secondary task would) should not impact performance to the same extent as for an explicitly trained skill. Similarly, for explicit monitoring to have a deleterious effect on performance, the performer must have awareness of the skill over which to (inappropriately) exert control. Conversely, the level of explicit skill knowledge should not play a large role in the extent of choking under pressure according to overmotivation theories. However, few studies have investigated how training strategies that seek to limit the amount of top-down control over behavior impact incentivized motor performance.

Here, we tested whether choking hinges on an attentional failure that is enabled by awareness, as would be predicted by distraction and monitoring theories, or if it is a more general feature of highly motivated motor performance, as predicted by overmotivation. In Experiment 1 we trained two groups of participants to perform a motor-sequencing task, either with sequence cues to promote the use of top-down strategies (*Instructed*) or incidentally to limit skill awareness (*Incidental*). All participants were trained on three separate sequences, but exposure to the three sequences was varied on the training day such that one sequence had been extensively trained, the second had only been moderately trained, and the third had been shallowly trained. Immediately following training, all participants performed the same task, with cash incentives contingent on successful performance. Previous work has shown that cash bonuses can induce performance pressure and lead to impairments in motor performance when monetary values are maximal (Ariely et al., 2009; Baumeister, 1984; Chib et al., 2012; Lee & Grafton, 2015; Mobbs et al., 2009). In addition to measuring accuracy and movement times, the use of a sequence-learning task afforded us the opportunity to examine the structure of learned movements (i.e., how a learned sequence is broken into discrete and reliable motor *chunks*) as a separate measure of performance.

In accordance with both distraction and monitoring theories, we hypothesized that only individuals who receive Instructed training would display the characteristic inverted-U-shaped signature of choking under pressure, whereby performance initially improves as the incentive values increase but then declines at high values. We anticipated that decreased performance under pressure would be marked by increased performance variability as assayed by an analysis of sequence chunking. Furthermore, we expected that if choking is due to explicit monitoring and not to distraction in this task, the most deeply trained sequence would be the one most vulnerable to pressure, as it would likely be the most proceduralized skill and should suffer most from interference via excess top-down control of learned movements. If both the Instructed and Incidentally trained participants choke under pressure, this would provide evidence for overmotivation theories of choking.

Experiment 1

Method

Participants

A total of 64 undergraduates from the University of California at Santa Barbara participated in Experiment 1 (36 females, 28 males; mean age = 19.5 years old; seven left-handed). Five additional participants were excluded because, during debriefing, they reported systematically looking away from the incentive value during its presentation. Each of these participants reported that they did not want to know when the trial was of high value, because they were worried that it would hurt their performance. Another was excluded because she reported that she had previously trained on a task similar to the discrete sequence production task in order to improve her typing skill. The sample size was determined so as to obtain a power of 0.8 using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007), assuming the effect sizes of choking under pressure from our prior published work on choking (Lee & Grafton, 2015).

Procedure and data analysis

Groups The participants in Experiment 1 were randomly assigned to one of two groups, Instructed or Incidental. The *Instructed* group (31 participants) received top-down cues to guide learning and performance, whereas the *Incidental* group (33 participants) did not. These manipulations are described in detail below.

Discrete sequence production task The task consisted of a modification of the discrete sequence production task that has been described previously (Verwey, Lammens, & van Honk, 2002). Four gray squares were statically presented on the screen as placeholders, corresponding to the four fingers of the hand (excluding the thumb). Participants were instructed to press a spatially compatible key (A, S, D, or F on a QWERTY keyboard) with their nondominant hand whenever one of the placeholders was illuminated white. We required the use of the nondominant hand in an attempt to further ensure that initial skill would be at a low level, and the position of the keyboard was adjusted such that each participant was centered in front of the computer screen in a comfortable position. As soon as the correct key had been pressed, the next square in the sequence lit up. After an incorrect keystroke, the corresponding square turned red for 1 s, and the trial was aborted. Failure to complete the sequence prior to the time deadline (8 s during training; individually calibrated during the reward phase) also resulted in an aborted trial, with an additional error message, "Too Slow," displayed for 1 s. All participants were exposed to three separate eight-item key sequences. These sequences were chosen to be free of trills (e.g., 1–2–1–2) and runs (e.g., 1–2–3).

Training blocks During training, all participants completed eight 40-trial blocks. In order to examine depth-of-training effects, three different sequences were trained in each block: (A) *deeply trained*—24 trials/block, 192 total; (B) *moderately trained*—12 trials/block, 96 total; (C) *shallowly trained*—four trials/block, 32 total. The order of sequences within each block was randomized. This manipulation was intended to vary the amount of proceduralization of each sequence-specific skill.

For participants in the Incidental training group, each trial began with a 2-s presentation of the placeholders prior to the illumination of the first item in the sequence (see Fig. 1a). In contrast, for participants in the Instructed training group, each trial began with a 1-s presentation of a colored square (yellow, blue, or green) that indicated the identity of the upcoming sequence, followed by a 1-s presentation of the placeholders.

The participants in the Instructed training group were told to learn the three sequences and their associated color cues. They were informed that the color cues would aid learning by helping them prepare their movements. Those in the Incidental training group were told that each trial would consist of eight randomly presented locations. All participants were told to respond as quickly and accurately as possible and that their movements would get faster during training. Additionally, all groups were told that this training period would be followed by a "test" period, without reference to performance-based cash bonuses.

Incentive blocks Immediately following training, participants were informed that they would next perform the same task with the possibility of earning cash bonuses. Participants completed 162 incentivized trials broken up into six 27-trial blocks. Each trial began with a 2-s presentation of the incentive value ($5, $10, or $20) associated with the upcoming trial, followed by a 1-s presentation of the placeholders prior to the illumination of the first item in the sequence (see Fig. 1b). The color cues indicating the sequence identity were presented simultaneously with the reward value for participants in the Instructed group. Incentive values were presented pseudorandomly, with a counterbalanced order of presentation (Buračas & Boynton, 2002). The order of the sequences (deep, moderate, or shallow training) was randomized and presented an equal number of times for each reward value. Participants were informed that at the end of the experiment one trial would be chosen at random and that if they had been successful on that trial they would receive its associated incentive value. This procedure ensured that the incentive for each trial was evaluated independently from those on other trials.

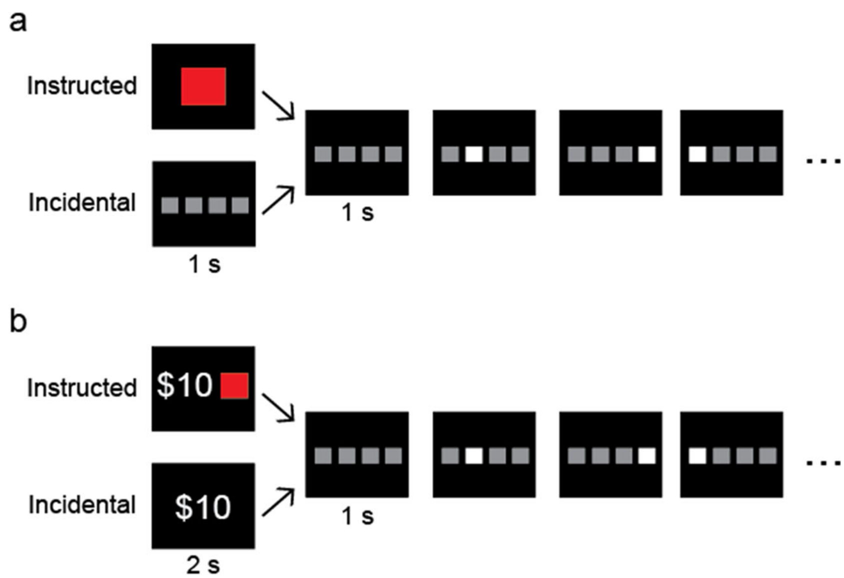

Fig. 1 Sequences of events in each (**a**) training trial and (**b**) incentive trial for the Instructed and Incidental groups

To match difficulty during incentivized performance across all sequences and all participants in both groups, a time limit was placed on each trial that was individually tailored for each sequence on a participant-by-participant basis relative to their skill level at the end of training (see the supplemental materials). This allowed us to use accuracy as a dependent measure, to compare accuracy across sequences both within and across individuals, and to avoid ceiling and floor effects. The imposition of strict time limits also helped guard against a speed–accuracy trade-off, whereby participants could intentionally slow motor execution in order to achieve success in the face of large rewards and/or performance pressure. This procedure was considered to have failed if a participant was unable to maintain performance above ~ 30% (2 *SD*s below the mean) on a sequence after the imposition of time limits. These data were removed from further analysis (six Instructed and four Incidental; average percent correct = 21.3%).

Sequence generation and recognition To assess the explicit knowledge of the sequences gained during the experiment, all participants received two separate memory tests at the end of the experiment: free generation and recognition (see the supplemental materials for complete details). We used the Damerau–Levenshtein edit distance between the freely generated sequences and the actual trained sequences to assess accuracy. This measure is simply equal to the minimum number of operations (insertions, deletions, substitutions, or transpositions) needed to transform one sequence into another. In the recognition task, participants were prompted to type out ten different eight-item sequences (seven novel, three old) and asked to rate on a 7-point Likert scale how likely they believed it was that the preceding sequence was old or new. Due to experimenter error, the recognition test was not administered to one Incidental participant.

Sequence chunking analysis

To get a more nuanced measure of motor performance, we used a Bayesian algorithm to estimate how participants chunked the sequences (see the supplemental materials and Acuna et al., 2014, for the complete methodological details). This algorithm exploits statistical regularities in the response times, errors, and their correlations to compute a distribution of how likely it is that each of a predefined set of chunking structures would be present at each trial. From this distribution, we estimated the strength and stability of the chunking behavior and calculated a "movement variability score," such that higher values indicated low chunking strength and a high degree of variability in how the sequence was chunked from trial to trial.

For three participants in the Instructed group and five participants in the Incidental group, the algorithm did not converge on a solution to reveal a reliable distribution of probable chunking structures for the three sequences. This was most likely due to a relatively small number of correctly completed trials. The data for these participants were excluded from this analysis.

Results

Instructed training resulted in enhanced learning

To assess the extent of learning during training, we examined the average movement times (MTs) between the initial key press and the eighth key press during each training block for each correctly performed sequence (Fig. 2). Average MTs were then entered into a repeated measures analysis of variance (ANOVA) with sequence identity and block as within-subjects factors and group (Instructed/Incidental) as a between-subjects factor. We found a significant main effect of training block [$F(3.79, 140.03) = 65.58$, $p < .001$, $\eta_p^2 = .639$;

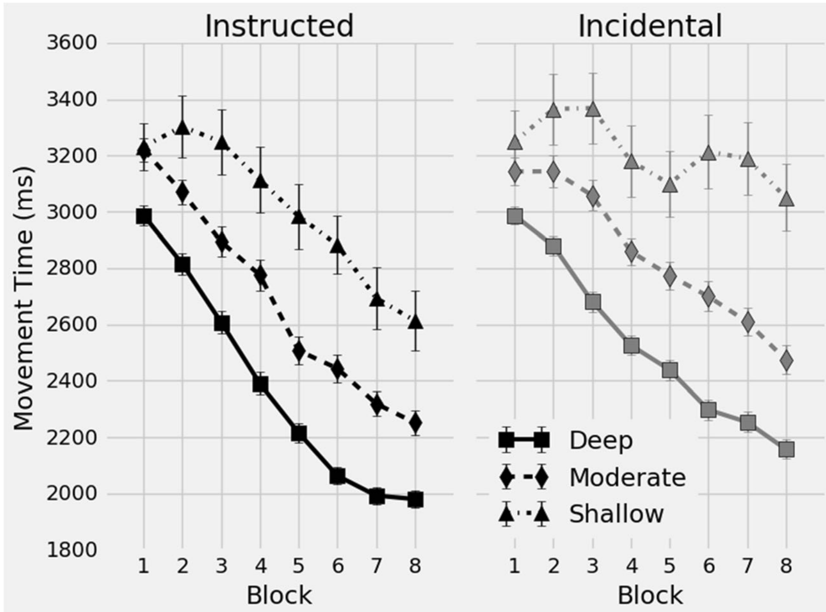

Fig. 2 Movement times across training blocks for correctly completed trials. Although both groups displayed evidence of learning in terms of decreased movement times over the time course of training, Instructed participants showed greater performance gains than did Incidental participants. Error bars are *SEM*s

Greenhouse–Geisser corrected, $\varepsilon = .541$], confirming an overall improvement in MTs over the time course of training. Additionally, this analysis revealed a significant main effect of sequence [$F(2, 74) = 102.01$, $p < .001$, $\eta_p^2 = .731$] and a Sequence × Block interaction [$F(7.57, 279.94) = 6.17$, $p < .001$, $\eta_p^2 = .143$, $\varepsilon = .540$], suggesting greater learning on more deeply trained sequences (difference in linear slopes across blocks: deep vs. moderate, $Z = 3.17$, $p < .005$; deep vs. shallow, $Z = 6.833$, $p < .001$; moderate vs. shallow, $Z = 4.47$, $p < .001$). Although the main effect of group was marginal [$F(1, 37) = 3.07$, $p = .088$, $\eta_p^2 = .077$], Instructed participants learned to a greater extent than did Incidental participants over the training blocks, as evidenced by a larger improvement in MTs [Group × Block interaction: $F(3.79, 140.03) = 4.78$, $p = .002$, $\eta_p^2 = .114$; difference in linear slopes across blocks: $Z = 5.56$, $p < .001$]. These results suggest that the explicit sequence cues enhanced sequence learning over the course of training.

Incidental training reduced explicit sequence knowledge

To test for differences in skill awareness between groups and across sequences, we entered the generation and recognition memory test results into an ANOVA with sequence as a within-subjects factor and group as a between-subjects factor. As we hypothesized, the participants in the Instructed group were better able to generate sequences from memory than were those in the Incidental group, suggesting a higher level of skill awareness [main effect of group: $F(1, 52) = 13.33$, $p < .001$, $\eta_p^2 = .204$]. There was also a small, but significant, overall main effect of sequence [$F(2, 104) = 3.79$, $p = .026$ $\eta_p^2 = .068$]. Post-hoc tests revealed that the generation of the moderately trained sequence was slightly more accurate than was that of the deeply and shallowly trained sequences (deep vs. moderate: $t = 2.17$, $p = .08$; deep vs. shallow: $t = 0.38$, $p = .92$; moderate vs. shallow: $t = 2.55$, $p = .03$). Furthermore, Instructed participants were better able than the Incidental participants to distinguish the three trained sequences from novel sequences in a recognition test [main effect of group: $F(1, 51) = 63.24$, $p = .01$, $\eta_p^2 = .122$]. However, both groups were able to distinguish all trained sequences from random sequences during recognition (t value range: 4.74–8.50, all ps $< .001$). Importantly, both memory tasks likely overestimate the level of explicit skill knowledge of the Incidental participants (see the supplemental materials). Therefore, the results from the two memory tests strongly suggest that the Instructed participants had more explicit skill knowledge than did the Incidental participants.

Only Instructed participants choked under pressure

Given both the distraction and explicit-monitoring theories, we hypothesized that only the Instructed group would be susceptible to the negative effects of performance pressure. Given that we imposed strict time limits during incentivized performance to protect against a speed–accuracy trade-off, we considered accuracy (the ability to correctly type a sequence under the time limit) as the main dependent variable of interest. We found no significant main effect of group during incentivized performance [$F(1, 52) = 0.699$, $p = .407$, $\eta_p^2 = .013$], suggesting that the time limits we imposed successfully matched difficulty between the two groups. Although the main effect of incentive was significant [$F(2, 104) = 3.63$, $p = .03$, $\eta_p^2 = .065$], this was driven by an Incentive × Group interaction [$F(2, 104) = 4.52$, $p = .013$, $\eta_p^2 = .080$], which confirmed that the participants in the Instructed group were more sensitive to the reward value than were the incidentally trained participants (Fig. 3). Analyzed alone, the Instructed group showed the characteristic inverted-U-shaped curve indicative of choking [main effect of reward: $F(2, 48) = 7.00$, $p = .002$, $\eta_p^2 = .226$; significant quadratic polynomial contrast: estimate = – 0.038, $t = – 3.54$, $p < .001$; nonsignificant linear contrast: estimate = 0.013, $t = 1.22$, $p = .23$]. Accuracy differed significantly between \$5 and \$10 ($t = 3.672$, $p = .002$), and also between \$10 and \$20 ($t = 2.46$, $p = .046$). There was no main effect of reward in the Incidental group [$F(2, 56) = 0.163$, $p = .850$, $\eta_p^2 = .006$]. These results indicate that limiting skill awareness was protective of choking under pressure.

Although we hypothesized that more deeply trained sequences might be more susceptible to incentive effects if choking were due to explicit monitoring, we did not find any significant main effects or interactions involving sequence identity [main effect of sequence in the Instructed group: $F(1.74, 90.27) = 0.701$, $p = .480$, $\eta_p^2 = .013$; Reward × Sequence interaction: $F(1.74, 90.27) = 0.312$, $p = .848$, $\eta_p^2 = .006$, $\varepsilon = .87$].

Although the time limits we imposed were intended to guard against a speed–accuracy trade-off and excessive slowing in the face of monetary incentives, we nevertheless conducted a repeated measures ANOVA on the MTs for correctly executed trials, with sequence identity and reward as within-subjects factors and group as a between-subjects factor. As expected, we found a significant main effect of sequence [$F(1.46, 76.12) = 94.737$, $p < .001$, $\eta_p^2 = .646$, $\varepsilon = .732$], whereby the more deeply trained the sequence, the more quickly it was executed (linear contrast A < B < C: $t = 13.76$, $p < .001$). Additionally, the Instructed group had faster MTs on the whole than did the Incidental group, as expected [main effect of group: $F(1, 52) = 5.69$, $p = .021$, $\eta_p^2 = .10$], which again points to the necessity of imposing participant-specific time limits on execution. Although we did not find a significant main effect of reward on MTs when both groups were analyzed together [$F(2, 104) = 2.09$, $p = .13$], we sought to confirm that the accuracy drop at the highest level of incentive in the Instructed group was not due to speeded execution. Although we did find a main effect of reward when the Instructed group was analyzed alone [$F(2, 48) = 4.37$, $p = .02$, $\eta_p^2 = .149$], this was strictly due to slow execution on \$5 trials, with no difference between the MTs on \$10 and \$20 trials (post-hoc tests: \$5 vs. \$10, $t = 2.60$, $p = .03$; \$5 vs. \$20, $t = 2.52$, $p = .04$; \$10 vs. \$20, $t = 0.07$, $p = .997$). These results again confirm that motor performance in the Instructed group improved as the incentive value increased from \$5 to \$10, but then performance began to collapse when the incentive value was maximal (\$20).

Instructed training led to increased variability in sequence chunking

We next assessed how Instructed and Incidental training impacted the movement variability during the incentive period by looking at chunking structure, using a repeated measures ANOVA with sequence as a within-subjects factor and group as a between-subjects factor. In the Incidental group, more

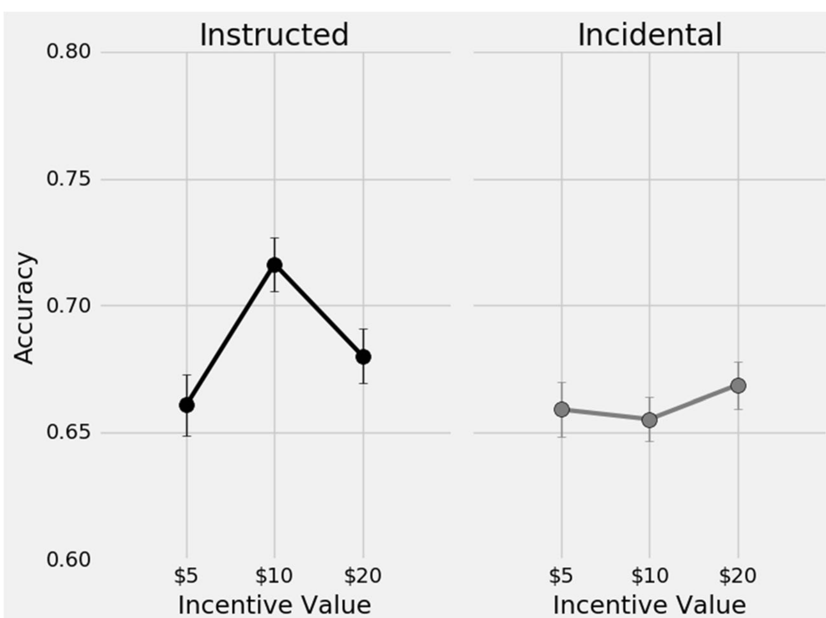

Fig. 3 Mean accuracies at each level of incentive. Only Instructed participants displayed evidence of choking under pressure. Error bars are normalized *SEM*s (Morey, 2008)

repetitions during training led to a stable chunking structure and less movement variability [main effect of sequence: $F(2, 44) = 17.93$, $p < .001$, $\eta_p^2 = .449$; linear contrast: estimate = 0.75, $t = 5.99$, $p < .001$]. This effect was not mirrored in the Instructed participants, who failed to show a depth-of-training effect [$F(1, 42) = 2.11$, $p = .13$, $\eta_p^2 = .09$]. Additionally, Instructed participants were found to be somewhat more variable overall [main effect of training group: $F(1, 42) = 3.49$, $p = .06$, $\eta_p^2 = .078$], and we found a significant Sequence × Group interaction [$F(2, 86) = 6.51$, $p = .002$, $\eta_p^2 = .132$; Fig. 4]. This interaction was driven by the fact that the more deeply trained sequences had a significant difference in movement variability across groups, in contrast to the shallowly trained sequence [Welch's unequal variances t tests between groups: deep, $t(23.15) = 3.56$, $p < .005$; moderate, $t(33.85) = 2.16$, $p < .05$; shallow, $t(42.96) = 1.71$, $p = .1$]. Although the Instructed participants improved to a greater extent during training, these chunking results suggest that they also showed greater instability in the nature of their performance for the more deeply trained sequences when faced with monetary incentives.

Experiment 2

The results from Experiment 1 suggest that increased top-down skill knowledge is associated with choking. However, the sequence identity cues were present during both learning and performance for the Instructed group and absent for both phases of the experiment for the Incidental group. It could be that the appraisal of, or the movement preparation afforded by, the sequence cues led to performance vulnerability during incentivized performance, regardless of the knowledge obtained during training. In other words, it was possible that the incidentally trained group would have choked under pressure if they had been given sequence cues during the incentivized phase of the experiment.

To rule this out, we ran a separate experiment in which sequence cues were added for incidentally trained participants following training (Incidental-Instructed) and removed for participants trained with the sequence cues (Instructed-Incidental). If the Incidental–Instructed participants were to perform poorly at high levels of incentive, it would suggest that Incidental training alone does not provide protection from choking under pressure. In contrast, if these participants were to maintain a high level of performance, this would be evidence that the nature of training itself was responsible for the results seen in the Instructed group in Experiment 1. Similarly, we would expect that Instructed training would lead to a reliance on top-down cues to drive successful performance and that the removal of these cues for the Instructed-Incidental group would greatly impair performance.

Method

Participants

A total of 43 undergraduates from the University of California at Santa Barbara participated in Experiment 2 (25 females, 18 males; mean age = 19.2 years old). All participants were right-handed and had normal or corrected-to-normal vision. No participant took part in both experiments.

Groups

Participants were randomly assigned to one of two groups (described in detail below): Instructed–Incidental (21 participants) or Incidental–Instructed (22 participants).

Procedure and data analysis

Experiment 2 incentive and cueing structure The training, time constraints, and incentive structure in Experiment 2 were identical to those aspects of Experiment 1, described above. Participants in the Incidental–Instructed group were trained incidentally but told immediately following training that they had actually been exposed to three separate sequences. They were shown each color cue and forced to correctly type the associated sequence a single time prior to the incentive phase of the experiment. The Instructed–Incidental participants were trained with the cues but subsequently told that the cues would be removed for incentivized performance. We additionally stressed that participants were to keep their eyes on the screen at all times. All other instructions and task parameters, including the time constraints, were otherwise identical to those aspects of Experiment 1. The participants in Experiment 2 essentially switched groups after training.

Analyses of variance All ANOVAs reported for Experiment 2 included sequence and reward as within-subjects factors. Where noted, group was included as a between-subjects factor. All significant effects are reported.

Results

Instructed training again led to enhanced learning

The training was virtually identical in Experiments 1 and 2, and unsurprisingly, the results across the two experiments were similar. We again submitted average MTs to a repeated measures ANOVA with sequence identity and block as within-subjects factors and group as a between-subjects factor. We found significant main effects of block [$F(7, 448) = 44.65$, $p < .001$, $\eta_p^2 = .583$] and sequence identity [$F(2, 64) = 118.03$, $p < .001$, $\eta_p^2 = .787$]. We also found a significant Sequence × Block interaction [$F(14, 448) = 3.58$, $p < .001$, $\eta_p^2 = .101$],

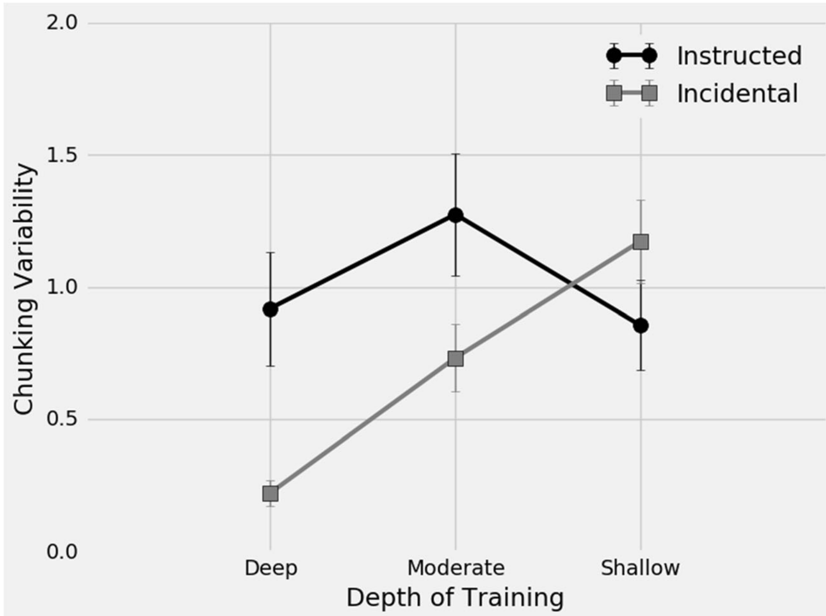

Fig. 4 Variability in chunking structure for each sequence. Deeper training led to increased chunking stability in the Incidental group. Instructed participants had more a variable movement structure than did Incidental participants. Error bars are *SEM*s

which again suggested that the learning curve was steepest for the more deeply trained sequences (differences in linear slopes across blocks: deep vs. moderate, Z = 1.18, $p = .24$; deep vs. shallow, Z = 3.90, $p < .001$; moderate vs. shallow, Z = 3.07, $p < .005$). Both groups displayed improvement over time, and greater exposure during training led to faster performance. The presence of a Block × Group interaction [$F(7, 224) = 2.64$, $p = .012$, $\eta_p^2 = .076$] again indicated that the presence of sequence cues during training led to greater learning (difference in linear slopes across blocks: Z = 3.48, $p < .001$).

Instructed training leads to a reliance on sequence cues

Removing the sequence cues following training in the Instructed–Incidental group had a profound effect on behavior during the incentive phase of the experiment (Fig. 5). The average accuracy rate across the group was ~36%, and only eight participants were able to maintain performance above 30% on all sequences (our criteria for inclusion). We did not exclude any participants from the subsequent analyses, since this appeared to be a facet of our manipulation. While there was no main effect of incentive nor evidence of choking when accuracy rates were entered into an ANOVA with reward and sequence as repeated factors [main effect of reward: $F(2, 40) = 0.537$, $p = .589$, $\eta_p^2 = .026$], these participants performed significantly worse than had the Instructed participants from Experiment 1, who received cues throughout both phases of the experiment [main effect of group: $F(1, 52) = 18.01$, $p < .001$, $\eta_p^2 = .257$; all Exp. 1 participants were included for this analysis, with group added as a between-subjects factor]. These results suggest that those participants who received sequence cues during training were heavily relying on those cues (and thus on top-down control) to guide performance.

The Instructed–Incidental participants also showed remarkably impaired performance when compared to the Incidental–Instructed group, who also had to deal with a change in cueing (main effect of group: $F(1, 41) = 39.11$, $p < .001$, $\eta_p^2 = .488$]. This Incidental–Instructed group showed no significant difference in overall or reward-specific performance as compared to the Incidental group from Experiment 1 [main effect of group: $F(1, 49) = 1.86$, $p = .18$, $\eta_p^2 = .037$; Group × Reward interaction: $F(2, 98) = 0.85$, $p = .43$, $\eta_p^2 = .017$] and also showed no main effect of incentive level [$F(2, 42) = 1.87$, $p = .17$, $\eta_p^2 = .082$]. This result strongly suggests that the impaired performance seen at high incentive values in the Instructed group from Experiment 1 was not due to the mere presence of sequence cues during incentivized performance. Instead, it seems that the type of training itself (i.e., Instructed or Incidental) profoundly affected the nature of how the skill was performed.

We did not find any significant or marginal effects in either memory task between the two groups in Experiment 2 (all *p* values greater than .5).

Discussion

In two experiments, we showed that participants trained incidentally on a motor-sequencing task displayed stable performance under pressure due to monetary incentives, even when they were subsequently given explicit top-down cues following training. Conversely, while participants who are trained to have deeper explicit sequence knowledge show an accelerated

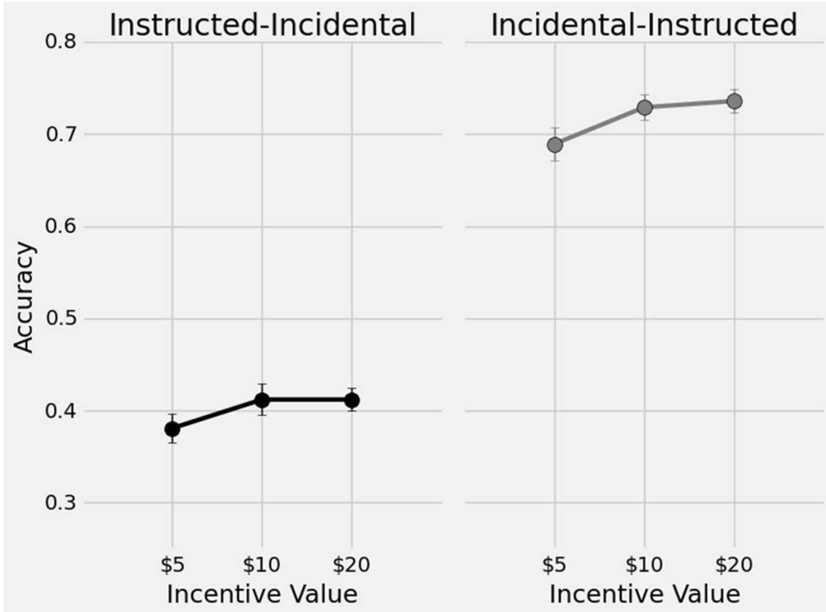

Fig. 5 Mean accuracies at each incentive level for the participants in Experiment 2. The Instructed–Incidental group showed markedly worse accuracy than did the Incidental–Instructed group and all participants in Experiment 1. Error bars are normalized *SEM*s

pace of learning, their performance relies on top-down cues (Exp. 2), and they subsequently choke under pressure, regardless of the amount of training received (Exp. 1). These results are most consistent with distraction theories of choking under pressure, which posit that choking reflects the involvement of top-down control processes during the execution of well-learned skills and that performance pressure occupies the resources necessary for performance.

Instructed participants not only showed impaired performance under pressure, but this vulnerability may have been linked to increased variability in performance consistency (i.e., chunking stability). Increased motor variability and poor performance under pressure have been observed previously in both golf and baseball (Cooke, Kavussanu, McIntyre, & Ring, 2010; Gray, 2004). However, we must note that we cannot determine from these results whether motor variability leads to impaired performance or is a consequence of it. Although the conscious intent to learn has been previously suggested to have minimal impact on chunking (Song & Cohen, 2014), the Bayesian framework used here may be more sensitive in detecting subtle changes in the structure and stability of motor chunks.

Intentional learning and awareness in sequence learning can be beneficial in the early stages of the skill acquisition process (Curran & Keele, 1993; Schendan, Searl, Melrose, & Stern, 2003; Willingham et al., 2002). Accordingly, we found that providing sequence cues to promote intentional learning coincided with more effective learning over the course of training (i.e., steeper learning curves, suggesting larger decreases in MT). Both the difference in sequence chunking between our groups and the poor performance of the Instructed–Incidental participants in Experiment 2 following removal of the sequence cues suggest that successful performance was driven by a reliance on these cues. Thus, distraction is plausible as a mechanism, in that the highest level of incentive might shift attention away from the cue or otherwise interfere with the top-down control processes necessary for performance.

Although Incidental participants displayed less skill knowledge than Instructed participants, they did have some limited knowledge of the trained sequences in that they reliably distinguished them from novel sequences. It is possible that the performance vulnerability under pressure in Instructed participants may not have been due to skill knowledge per se, but instead have been the outcome of cognitive processing or movement preparation, which, although sometimes advantageous, are vulnerable to performance pressure. Movement strategies that initially aid action may subsequently be detrimental to performance in certain circumstances if they work to block the execution of well-learned procedural skills (e.g., Beilock, Carr, MacMahon, & Starkes, 2002; Mazzoni & Krakauer, 2006). Therefore, it could be that execution itself is unaffected, but the motor plan selected for execution is suboptimal.

We had initially hypothesized that, in accordance with explicit-monitoring theories of choking, sequences that were trained more extensively would be more vulnerable to performance pressure. However, incentivized performance did not differ on the basis of depth of training. While our results are thus most consistent with distraction theories of choking under pressure, we cannot entirely rule out explicit-monitoring accounts of choking. Prior work has shown that using performance-contingent monetary incentives to induce performance pressure, as we did here, is more likely to lead to choking via distraction, whereas the presence of an audience leads to explicit monitoring (DeCaro, Thomas, Albert, & Beilock, 2011). It is possible that a different pressure manipulation in this task (e.g., social-monitoring pressure) would have provided stronger evidence for explicit monitoring.

Additionally, prior studies have shown that explicit monitoring has more detrimental effects for expert performers, but distraction has a greater impact on novices (Beilock & Carr, 2001; Worthy, Markman, & Maddox, 2009). Although the depth-of-training manipulation was designed in an attempt to dissociate expert and novice skills, all training in the experiments presented here occurred for less than 1 h on a single day and may have been insufficient to produce any effects of expertise. Motor learning is thought to occur along multiple time scales, with differential contributions of separable neural systems contributing in parallel. Sequence representations themselves can be identified in prefrontal areas early on in long-term sequence training over several weeks (Wymbs & Grafton, 2015). With more extensive training, sequence-specific representations are primarily localized to primary motor and ventral premotor cortices. Given the role of the prefrontal cortex in top-down control, this shift out of prefrontal cortex might suggest that extensively trained individuals should be immune to performance collapse. However, many studies have shown that highly expert performers can be induced to choke (e.g., Gray, 2004), leading several researchers to suggest that performance vulnerability in experts may reflect a return to a mode of control akin to what had been used effectively in the early phase of skill acquisition (Beilock & Gray, 2012; Masters, 1992). Although extended training is likely to diminish the likelihood of returning to this mode of control, it remains possible that instances of performance pressure might affect individuals differentially and depend on training regimes. Although the overall performance differences between Instructed and Incidental converged, we speculated that Incidental training, especially early on in skill acquisition, might lead to more robust retention and resilience to distracting performance pressure.

While we assume that the different levels of incentive produced similar psychological and physiological effects across both the Instructed and Incidental groups, we did not collect heart rate, pupillometry, or other behavioral/physiological measures of arousal to confirm the effects of performance pressure induced by large incentives. It is possible that the type of skill training encountered might have led participants to interpret the incentive cues in subtly different ways. Future work incorporating physiological measures could serve to shed light on specific interactions between physiological arousal, training, and performance under pressure.

Our results suggest that targeted training strategies may be able to ameliorate performance vulnerability under pressure. Several studies have shown that rule-based instruction, attention to motor execution, and the step-by-step control of movements can sometimes have negative impacts on performance (Beilock et al., 2004; Masters, 1992; Wulf & Prinz, 2001). Along with this prior work, our results lead us to conclude that a training regime that seeks to restrict awareness of movement strategies and structure could lead to more stable performance under pressure, potentially via reduced performance deficits in the face of distraction.

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