Automatization and deautomatization of perceptual-motor skills

Koedijker, J.M.

2010

Chapter 3

Table tennis performance following explicit and analogy learning over 10,000 repetitions

This chapter is published as:

Koedijker J. M., Oudejans R. R. D., & Beek P. J. (2008). Table tennis performance following explicit and analogy learning over 10,000 repetitions. *International Journal of Sport Psychology, 39,* 237-256.

Abstract

We investigated acquisition and performance during explicit and analogy learning over many repetitions, with a specific interest in changes in the robustness of performance under increased pressure. Explicit and analogy learning groups performed 10,000 table tennis forehand strokes, evenly distributed over six weekly sessions. Explicit learners reported more explicit rules about movement execution than analogy learners, even though this number declined from 1,400 to 10,000 repetitions. Furthermore, performance of the analogy group seemed to asymptote after 1,400 repetitions, while that of the explicit group continued to increase. Despite differences in rule formation, neither group appeared to show performance decrements under pressure or secondary task loading after 1,400 or 10,000 repetitions. All in all these findings do not provide grounds for minimizing the accumulation of explicit knowledge in learning in view of its potentially detrimental effects on performance.

Introduction

Providing verbal instructions is a common practice in many forms of perceptual-motor teaching under the supervision of a coach or trainer. In the course of skill acquisition, such instructions amass to a pool of explicit knowledge, that is, knowledge about movement execution that the learner is aware of and thus can verbalize. In recent years, however, the effectiveness of providing verbalizable rules in perceptual-motor acquisition has been questioned. Evidence has been presented indicating that withholding learners from accruing explicit rules about movement execution results in performance advantages when performance pressure increases or when performing under secondary task loading (Koedijker, Oudejans, & Beek, 2007; Liao & Masters, 2001; Masters, 1992; Poolton, Masters, & Maxwell, 2005; Poolton, Maxwell, Masters, & Raab, 2006).

To explain these findings, it has been argued that under increased performance pressure, stored explicit rules can be activated in working memory to interfere with proceduralized movement control, thereby disrupting fluent and automated movement execution (Masters & Maxwell, 2004). This line of reasoning is known as the reinvestment or explicit control hypothesis. The greater dependence of explicitly learned skills on working memory would also result in a capacity overload when a secondary task is introduced, whereas implicitly learned skills would allow execution of a secondary task without performance decrements as a result of reduced demands on working memory. The aforementioned evidence of impaired performance of explicitly learned skills under certain demanding circumstances suggests that working memory involvement in learning is not necessarily advantageous. However, in an unrestricted environment, perceptual-motor learners are bound to test movement-related hypotheses in working memory, potentially leading to the accumulation of explicit rules about movement execution (Hardy, Mullen, & Jones, 1996; Masters, 1992). To insure that learning is implicit, such hypothesis testing should be prevented. Masters (1992) proposed that this can be achieved by overloading working memory during skill learning. In particular, he demonstrated that when learners perform a concurrent secondary task during primary skill learning, minimal explicit knowledge about movement execution is accumulated and primary task performance is robust to increases in performance pressure. As implicit learning with a dual task is rather impractical (Bennett, 2000), and suffers from below average performance improvement during learning (Masters, 1992; Maxwell, Masters, & Eves, 2000), several alternative methods of implicit learning have been proposed and tested, such as analogy and errorless learning (see Liao & Masters, 2001; Maxwell, Masters, Kerr, & Weedon, 2001, respectively). In analogy learning, only one simple, but biomechanically adequate rule is provided. By following this single rule, learners also forego hypothesis testing about their behavior, leading to little accrual of explicit knowledge about movement execution. For instance, Liao and Masters (2001) provided participants with a triangle analogy to help them learn the table tennis forehand. In particular, they instructed participants to pretend drawing a right-angled triangle and hitting the ball while traveling along the imaginary hypotenuse. It appeared that analogy learners accumulated few explicit rules about movement execution yet demonstrated similar learning performance and robustness to performance pressure as explicit learners.

So far, however, the studies that have demonstrated advantages of implicit over explicit learning (most notably robustness to performance pressure) involved a maximum of 500 repetitions (e.g., Hardy et al., 1996; Koedijker et al., 2007; Liao & Masters, 2001; Masters, 1992). Only Maxwell et al. (2000) compared implicit and explicit learning over markedly more repetitions (3000 golf putts) but found no differences in performance between implicit and explicit learners on a low pressure retention test. However, as they did not investigate performance under high pressure, it remains unclear whether there is a difference in robustness under pressure between performance of implicit and explicit learners during many repetitions.

In general, it is known that millions of repetitions are required to reach top levels of perceptual-motor performance (Crossman, 1959; Kottke, 1980). This is in line with ideas and findings concerning deliberate practice underscoring that expert athletes and artists practice for at least 10 years for an estimated number of 10,000 hours before reaching their peak (Ericsson, 1996; Ericsson, Krampe, & Tesch-Römer, 1993; Hodges & Starkes, 1996; Starkes, 2000). Kottke (1980) argued that minimally 10,000 repetitions are needed to come to “a fair engram” (p. 559) and to produce the first signs of automatic movement execution. In short, it seems reasonable to argue that after a mere 500 repetitions, learners may still be considered novice performers. According to theoretical accounts of skill acquisition, the first stage of perceptual-motor learning is characterized by (a need for) conscious foreground corrections in movement control (Anderson, 1982; Bernstein, 1967; Fitts & Posner, 1967; Willingham & Goedert-Eschmann, 1999), as has been confirmed empirically, among others, by Beilock and colleagues (Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002). If explicit learners can still be considered novices after less than 500 repetitions of learning, then their performance should be harmed by the introduction of a secondary task as their movement execution is not yet automatized, as indeed appears to be the case (Koedijker et al., 2007; Liao & Masters, 2001; Poolton et al., 2005; Poolton, Maxwell, et al., 2006).

In the present study we therefore tested the reinvestment hypothesis by comparing acquisition and performance during explicit and analogy learning while achieving more proficient, and more automatized behavior. To this end, participants practiced the table tennis forehand over 10,000 repetitions either with a set of explicit instructions (explicit group) or with a single instruction in the form of an analogy (analogy group) during six training sessions that were evenly distributed over a 6-week period. Acquisition measurements (low pressure) were taken at the beginning, and after 1,400, 6,300 and 10,000 repetitions. Performance was measured using a combination of accuracy and movement execution (cf. Koedijker et al., 2007; Liao & Masters, 2001). Overall, we had no reason to presume that learning progression would be different for the two groups. As in the study of Masters (1992), the number of explicit rules was assessed by means of a verbal protocol that required participants to write down every aspect of movement execution that they were aware of doing or were using during performance. This verbal protocol was administered after 1,400 (end of Session 1) and 10,000 (end of Session 6) repetitions, and it was expected that the explicit group would have accumulated more explicit rules than the analogy group over 10,000 repetitions. In addition, after 1,400 and 10,000 repetitions, participants were tested under dual task and high pressure conditions. The dual task condition was included to determine the degree of automatization. It was hypothesized that after 10,000 repetitions, performance of both groups would be automatized to an equal extent, and thus, be unharmed by a secondary task. According to the reinvestment hypothesis, the performance of explicit learners, having accumulated ample explicit rules, would decrease when facing increased pressure, whereas the performance of analogy learners would remain unaffected under such circumstances.

Method

Participants

Fifteen individuals (2 men, 13 woman) between 17 and 29 years of age (*mean* = 19.6, *SD* = 3.4) participated in the experiment. The participants had little or no experience in table tennis, that is, having never received any form of instruction or practiced or played more than once a fortnight. They were randomly divided in two groups: an explicit learning group (EG, *n* = 8) and an analogy learning group (AG, *n* = 7).

Experimental set-up

A table tennis robot (Donic Robopong 2040) was positioned behind a table tennis table (Tiga, mega CS) at the side of the table opposite to that of the participant. The target, also located at the opposite side of the table, consisted of three concentric circles with diameters of 9.5, 20.0 and 30.5 cm, respectively. A VHS camcorder registered the landing position of the ball. This camera could be seen by the participant but its presence was not distracting as it was directed at the table. A second camera (DV camcorder) was placed behind the participant and fully covered the experimental set-up. In the high-pressure test another DV camera was positioned directly in front of the participant to increase perceived self-awareness. A table tennis bat from the Donic 700 series was used.

Task

Participants stood opposite the ball machine and were instructed to hit the ball diagonally across the table to the target.

Design and procedure

The EG received an explicit set of instructions about how to execute the table tennis forehand, which were drawn and translated from a guidebook (Hodges, 1993; see Appendix A of Chapter 2) and subsequently checked by an experienced coach (cf. Koedijker et al., 2007). The AG received only a single instruction in the form of an analogy. Participants were instructed to pretend drawing a right-angled triangle with the bat. They were instructed to move the bat backwards over the bottom of the triangle and to then hit the ball while moving up along the hypotenuse (cf. Liao & Masters, 2001). Participants were reminded of their respective instructions before each block of 100 repetitions (see below). Furthermore, the respective instructions were available for the participants (either as a list of explicit rules or a picture of the analogy) during the entire experiment.

The experiment was performed over six sessions of about one hour administered once a week during a six-week period. During the first session (S1), the participants performed 15 practice trials to get used to the experimental task and set-up followed by a pre-test (PT). The PT consisted of 50 repetitions under the sole instruction to hit the target as accurately as possible. After the PT, the relevant instructions were given. The PT was followed by a first learning session consisting of 14 blocks of about 100 repetitions with a 10-minute break after the seventh block. Throughout the experiment each block lasted two minutes with balls being fed to the participant at a frequency of 50 per minute. Pilot testing had demonstrated that with this frequency participants could still readily return to the start position before the next ball was delivered without compromising task execution. Before the start of each block, participants were reminded of their respective instructions.

The first learning session (S1) was followed by three tests: a low-pressure test (LPT), a high-pressure test (HPT) and a dual-task test (DTT), each consisting of 50 trials. For the LPT initially 100 trials were executed on each occasion as participants had to remain unaware of the fact that they were being tested.

Therefore, after the 14th block of training, participants were informed that the upcoming block would be their last training block for the day. No additional information or instructions were given. Only the first 50 repetitions of this block were used as the LPT, because these would compare best to PT, HPT and DTT, which all consisted of 50 trials (note that 50 rather than 100 trials were used in the tests because data analyses of task performance involved two sets of time-consuming video analyses, see *Dependent Variables and Data Reduction*). The HPT and DTT were conducted after the LPT and were counterbalanced to eliminate order effects. To increase pressure in the HPT participants were told that the next block was intended to determine how well they had learned their table tennis forehand and that they could win a prize if a certain target score was realized. The target score was set at the estimated score of the LPT counted in silence by one of the experimenters. During the HPT a camera was placed conspicuously in front of the participant to increase self-awareness (cf. Hardy et al. 1996; Masters, 1992). In addition, scores were counted aloud by the experimenter in an attempt to increase pressure even further. Although in principle the counting out loud of the scores of each shot could have created a distraction, it was not strictly necessary for the participants to attend to the counting of scores as knowledge of the result was also provided by visual feedback, effectively placing little cognitive demand on the participant. In addition, in an earlier study the same pressure manipulation, including the counting out loud, resulted in higher anxiety scores as well as a degradation of performance for an explicit learning group (Koedijker et al., 2007), providing confidence in our pressure manipulation. During the DTT participants were instructed to count aloud backwards from 1,100 in steps of 3 while performing the table tennis forehand. Counting backwards is an attention-consuming task, which has already been demonstrated to be suitable for testing working memory involvement and automatization of task execution in perceptual-motor tasks (Koedijker et al., 2007; Lewis & Linder, 1997; MacMahon & Masters, 2002).

Sessions 2 and 3 were training sessions consisting of 15 blocks of 100 repetitions each with a 10-minute break after Block 7. Sessions 4 and 5 were training sessions consisting of 20 blocks of 100 repetitions with a 10-minute break after Block 10. Furthermore, the last block of training of Session 4 (S4) was used as an extra measurement of low pressure learning performance. Session 6 (S6) was equal to Session 1 (S1), except that there was no pre-test. All in all, this resulted in 10,000 practice repetitions before the second post-test stage, which consisted of a second low-pressure, high-pressure and dual-task test, each consisting of 50 trials, similar to the tests at the end of S1.

Dependent variables and data reduction

To check whether the pressure manipulation was successful, subjectively experienced anxiety was measured using an anxiety thermometer in the form of a visual analogue scale ranging from 0 ('not nervous at all') to 10 ('very nervous'). The validity and test-retest reliability of the anxiety thermometer are fair, with correlation coefficients ranging between .60 and .78 (Houtman & Bakker, 1989). Unlike the often used Competitive State Anxiety Inventory-2 (CSAI-2, Martens, Vealy, & Burton, 1990), the anxiety thermometer provides a quick and reliable way to measure state anxiety (cf. Pijpers, Oudejans, Bakker, & Beek, 2006). In this context, it should be noted that the anxiety thermometer does not take into account the distinction between cognitive and somatic anxiety as measured with the CSAI-2. However, anxiety thermometer scores appear to correlate equally with cognitive anxiety scores and somatic anxiety scores on the CSAI-2, r = .59 versus r = .62, respectively (Bakker, Vanden Auweele, & van Mele, 2003). For each measurement and each individual, a separate anxiety thermometer was used. The anxiety thermometer was applied directly after the LPT and HPT of both S1 and S6. Participants were asked how anxious they felt during the test they had just performed. Houtman and Bakker (1989) and Bakker et al. (2003) showed that there are relatively high correlations (mostly above .70) between anxiety scores taken before or after an event providing support for the validity of a measurement procedure in which feelings of anxiety are obtained after the event. To assess an increase in performance pressure from the LPT to HPT, analyses of variance (ANOVA) with repeated measures on the various test conditions were employed.

To assess the number of explicit rules, participants were required to write down a detailed description of how they had executed the forehand stroke upon completion of the first post-test stage (i.e., after 1,400 repetitions) and after the second post-test stage (i.e., after 10,000 repetitions). For the purpose of analyzing the written reports an inventory was made of all possible aspects of movement execution, which were then categorized as either being related to the environment (external) or the movement itself (internal). We hereby made a clear distinction between rules specifically related to movement execution (internal, e.g., "I keep my wrist firm"), and task- but not movement-related rules (external, e.g., "I look at the target"), see Koedijker et al. (2007). Two independent observers scored the number and categorization of the explicit rules with low percentages error, 3.6% for the total number of rules and 0% for the categorization, as a reliable measure of inter-observer reliability (see Hughes & Franks, 2004). Numbers of explicit rules averaged over the two observers were used for further analysis. To examine differences in average number and categorization of the explicit rules, repeated measures ANOVAs were performed.

To eliminate the possibility that differences in performance scores between groups in the DTT resulted from differences in performance on the secondary task, one-way ANOVAs were conducted on the percentage of correct responses and the average response time on the secondary task (both obtained from video), respectively.

Actual table tennis performance was operationalized as the combined score of accuracy and movement execution similar to the performance score used by Liao and Masters (2001) and Koedijker et al. (2007). Accuracy was determined from the video recordings of the landing positions of the ball. When the ball landed in the smallest circle four points were awarded; hitting the middle circle yielded three points and hitting the largest circle yielded two points. Returning and placing the ball on the table at the opposite side of the net without hitting one of the targets gained the participants one point. Otherwise no points were scored. A selection of 100 scores was rated by two independent observers. As a reliable measure of inter-rater reliability we computed the percentage error between the scores of the two observers (see Hughes & Franks, 2004), resulting in an acceptable 4.0 % error.

The quality of movement execution was quantified with scores ranging from 0 to 3 on the basis of the video recordings. The scores were operationalized as follows: a score of 0 meant no proper forehand execution at all; a score of 1 meant executing a forehand with a rigid trunk and without a follow-through (swinging the arm further after hitting the ball) longer than approximately 15 cm (about the size of the blade of the bat); a score of 2 meant executing a forehand with a follow-through larger than 15 cm, but still no full swing (rigid trunk); a score of 3 meant a full swing of the arm and rotation of the trunk. The scoring system was established following consultation with a table tennis expert. A second independent observer also scored a selection of 160 movements (five trials of each of the eight tests of four randomly chosen participants). As these were not just frequency counts percentage error could not be computed. Instead, we determined the percentage of inter-observer agreement, which was 96%.

The eventual performance score used was the product of accuracy and quality of movement execution, but separate analyses for accuracy and movement execution scores are presented as well to provide more insight into our findings. Specific ANOVAs with repeated measures were employed to test for performance changes between the different tests. Recall that there were four low-pressure measurements of learning performance: PT, S1, S4 and S6. To test for differences in learning progression between the groups, scores on PT, S1, S4 and S6 were compared. If the sphericity assumption was violated, either the Huynh-Feldt correction (if Greenhouse-Geisser's epsilon $< .75$) or the Greenhouse-Geisser correction (if Greenhouse-Geisser's epsilon > .75) was used (Girden, 1992). To test for effects of performance pressure, scores on LPT and HPT of S1 and S6 were compared and the effects of secondary task loading were tested by comparing LPT and DTT of S1 and S6. For all ANOVAs effect sizes were calculated using Cohen's *f* statistic (Cohen, 1988). By convention, a Cohen's *f* of 0.10 represents a small effect, an *f* of 0.25 a medium effect and an *f* of 0.40 a large effect (Cohen, 1988).

Results

Perceived performance pressure

To examine whether the pressure manipulation was successful, the subjectively perceived anxiety scores were submitted to a Group (EG, AG) × Test (LPT, HPT) × Session (S1, S6) ANOVA with repeated measures on the last two factors. This analysis revealed a significant and large effect of test ($F_{1,\,14} = 22.84$, $p < .001$, $f = 1.32$). On average, the HPT was experienced as more stressful ($M = 1.98$, $SD = 1.53$) than the LPT ($M = 0.51$, $SD = 0.58$) without any significant differences between groups or sessions (*F*s < 1.26, *p*s > .28, *f*s < 0.30).

Number and direction of explicit rules

Table 3.1 shows the numbers of internal and external rules that were reported after 1,400 and 10,000 repetitions respectively. To examine whether the different instructions led to differences in explicit rule formation, a Group (EG, AG) × Session (S1, S6) × Type (internal, external) ANOVA with repeated measures on the last two factors was performed on the number of explicit rules. It yielded significant effects of group ($F_{1,13} = 19.52$, $p < .01$, $f = 1.22$), session ($F_{1,\,13} = 8.05$, $p < .05$, $f = 0.79$), type ($F_{1,13} = 91.01$, $p < .001$, $f = 2.65$), Group × Type ($F_{1,13} = 19.40$, $p < .01$, $f = 1.22$) and Session × Type ($F_{1,13} = 11.74$, $p < .01$, $f = 0.95$), as well as a marginally significant Group × Session interaction ($F_{1,13} = 4.03$, $p = .066$, $f = 0.56$). However, all these effects were superseded by a significant Group × Session × Type interaction with a large effect size ($F_{1,13} = 15.14$, $p < .01$, $f = 1.08$). These analyses indicated that our attempt to discriminate between explicit and implicit learning had been successful in that the explicit learners reported more explicit rules than the implicit learners.

Subsequently, two Session (S1, S6) × Type (internal, external) ANOVAs were executed for each group separately to investigate the three-way interaction in more detail. The ANOVA for the EG yielded main effects for session ($F_{1,7} = 14.58$, $p < .01$, $f = 1.44$) and type ($F_{1,7} = 67.18$, $p < .001$, $f = 3.10$), as well as a significant interaction, ($F_{1,7} = 29.84$, $p < .01$, $f = 2.06$). Pair-wise comparisons using the Bonferroni correction procedure showed that the number of internal explicit rules reduced from 1,400 to 10,000 repetitions for the EG ($p < .05$; see Table 2.1), but not for the AG. The ANOVA for the AG only yielded a significant effect of type, ($F_{1,6} = 34.56$, $p < .01$, $f = 2.40$), indicating that there were more internal than external explicit rules at both test sessions (see Table 2.1), but no changes in numbers of rules from the first to the second test session (Fs < 0.27, $ps > .62$, fs < 0.21).

Table 3.1. Means ± standard deviations of the number and direction of explicit rules on both post-test assessments for the different groups

	post-test 1,400		post-test 10,000	
Group	internal	external	internal	external
EG	7.13 ± 2.30	0.38 ± 0.52	4.75 ± 1.75	0.25 ± 0.46
AG	2.43 ± 1.51	0.43 ± 0.79	2.29 ± 0.49	0.14 ± 0.38

Table tennis performance

*Acquisition.*To test for learning effects, a Group (EG, AG) × Session (PT, LPT of S1, S4 and LPT of S6) ANOVA was performed on the performance scores with repeated measures on the last factor. It yielded a significant effect of session ($F_{2.09,27.21} = 31.41$, $p < .001$, $f = 1.55$), as well as a marginally significant Group × Session interaction ($F_{3,39} = 2.73$, $p = .057$, $f = 0.46$), but no significant effect of group ($p = .69$, $f = 0.10$). Pair-wise comparisons with Bonferroni corrections indicated that the EG continued to improve their performance between 1,400 and 6,300 repetitions ($p < .05$) before leveling off (from 6,300 to 10,000 trials, $p = .64$), whereas performance of the AG already seemed to level off after 1,400 trials (ps > .76; see further Table 3.2a).

To find out whether this difference between EG and AG was the result of differences in movement execution, accuracy, or both, separate analyses were performed for movement execution and accuracy. For movement execution, a Group (EG, AG) × Session (PT, LPT of S1, S4 and LPT of S6) ANOVA with repeated measures on the last factor was performed. It revealed significant effects of session ($F_{1.99,25.85} = 28.66$, $p < .001$, $f = 1.41$) and group ($F_{1,13} = 6.63$, $p < .05$, $f = 0.80$) as well as a significant Group × Session interaction ($F_{3,39} = 3.92$, $p < .05$, $f = 0.54$). Pair-wise comparisons with Bonferroni corrections indicated that the EG and AG did not differ in movement execution scores between 0 and 1,400 repetitions (ps > .27), but that the EG demonstrated a better movement execution after 6,300 and 10,000 repetitions (ps < .05; see Table 3.2b). For accuracy, a Group (EG, AG)

× Session (PT, LPT of S1, S4 and LPT of S6) ANOVA was performed with repeated measures on the last factor. It only revealed a significant effect of session ($F_{2.51,27.97} = 15.84$, $p < .001$, $f = 1.08$), without any significant group effects or interactions (Fs < 2.03, ps >.18, fs < 0.39). Pair-wise comparisons with a Bonferroni correction revealed that performance accuracy improved from 0 ($M = 1.15$, $SD = 0.57$) to 1,400 ($M = 1.70$, $SD = 0.49$) repetitions without any differences between groups or further improvement beyond 1,400 repetitions (see Table 3.2c). Thus, together these analyses show that the EG continued to improve in performance score between 1,400 and 6,300 because of an improved movement execution rather than improvements in accuracy.

Table 3.2a. Means ± standard deviations of the performance scores for the different groups for all tests

	PT	Post test 1,400			S4	Post test 10,000		
		LPT	HPT	DTT		LPT	HPT	DTT
EG	1.33 ± 0.73	4.09 ± 1.60	4.84 ± 2.00	3.84 ± 1.87	5.48 ± 1.05	5.56 ± 0.95	6.38 ± 1.46	4.84 ± 1.21
AG	1.94 ± 1.48	4.67 ± 2.35	5.10 ± 2.48	4.47 ± 2.31	4.55 ± 1.37	4.42 ± 1.53	4.99 ± 1.46	4.24 ± 1.06

Table 3.2b. Means ± standard deviations of the movement execution scores for the different groups for all tests

	PT	Post test 1,400			S4	Post test 10,000		
		LPT	HPT	DTT		LPT	HPT	DTT
EG	1.25 ± 0.38	2.72 ± 0.70	2.50 ± 0.76	2.67 ± 0.71	3.00 ± 0.00	3.00 ± 0.00	2.88 ± 0.35	2.88 ± 0.35
AG	1.43 ± 0.53	2.29 ± 0.76	2.29 ± 0.76	2.29 ± 0.76	2.29 ± 0.76	2.14 ± 0.69	2.14 ± 0.69	2.14 ± 0.69

Table 3.2c. Means ± standard deviations of the accuracy scores for the different groups for all tests

	PT	Post test 1,400			S4	Post test 10,000		
		LPT	HPT	DTT		LPT	HPT	DTT
EG	1.10 ± 0.54	1.49 ± 0.39	1.89 ± 0.36	1.44 ± 0.52	1.83 ± 0.35	1.85 ± 0.31	2.23 ± 0.45	1.68 ± 0.33
AG	1.21 ± 0.65	1.95 ± 0.52	2.17 ± 0.56	1.91 ±0.31	1.99 ± 0.45	2.08 ± 0.28	2.35 ± 0.22	2.03 ± 0.24

Dual-task performance. The dual-task condition was included to examine whether we achieved more expert, automatized movement control for both groups after 10,000 repetitions. As for performance on the secondary task, on average participants gave 29.2 counting responses during the one-minute DTT (one every 2.0 seconds), of which on average 2.8 (SD = 2.5) was incorrect. Two Group (EG, AG) × Session (S1, S6) ANOVAs with repeated measures on session for average response time and percentage of incorrect responses on the secondary task revealed no significant effects, Fs < 0.77, ps > .39, indicating that the secondary task was conscientiously and effectively executed by both groups and on both sessions.

To examine the effects of the secondary task loading on table tennis performance, a Group (EG, AG) × Session (S1, S6) × Test (LPT, DTT) ANOVA was performed on performance scores with repeated measures on the last two factors. Although the effects of test and the Group × Session interaction had a large effect size (f = 0.45, and f = 0.40, respectively), they did not reach significance ($F_{1,13}$ = 2.72, p = .12, and $F_{1,13}$ = 2.14, p = .17, respectively). All other differences were non-significant and had medium or small effect sizes (Fs < 1.15, ps > .31, fs < .29). These results suggest that secondary task loading did not significantly affect overall performance of the two groups, neither on S1 nor on S6 (see Table 3.2a). A separate Group (EG, AG) × Session (S1, S6) × Test (LPT, DTT) ANOVA on movement execution scores only revealed a significant effect of group ($F_{1,13}$ = 5.41, p < .05, f = 0.70), with the EG performing better on average (M = 2.81, SD = 0.44) than the AG (M = 2.21, SD = 0.72), as was also already established for acquisition. All other effects were non-significant (Fs < 1.58, ps > .23, fs < 0.35) again suggesting that the secondary task had no negative effect. The separate Group (EG, AG) × Session (S1, S6) × Test (LPT, DTT) ANOVA on accuracy scores yielded a significant effect of group ($F_{1,13}$ = 5.23, p < .05, f = 0.63) as well as a marginally significant effect of session ($F_{1,13}$ = 3.89, p = .07, f = 0.54). All other effects were non-significant (Fs < 1.50, ps > .24, fs < 0.34)**.** The significant main effect of group revealed that on average the AG (M = 1.99, SD = 0.41) performed more accurate than the EG (M = 1.61, SD = 0.39). Furthermore, it seems that participants performed more accurate on S6 (M = 1.91, SD = 0.31) than S1 (M = 1.68, SD = 0.43). Again, a lack of significant effects involving test seems to confirm that the secondary task had little effect on performance. Since all three analyses produced no significant main effects or interaction effects in which the factor test was involved, we feel it is safe to assume that even already after 1,400 repetitions table tennis performance was indeed equally automatized in both groups.

*Performing under pressure.*To test for the effects of pressure on performance, a Group (EG, AG) × Session (S1, S6) × Test (LPT, HPT) ANOVA with repeated measures on the last two factors was performed on performance scores. The analysis yielded a significant effect of test ($F_{1,13}$ = 13.87, p = .01, f = 1.03). Furthermore, the Group × Session interaction had a large effect size, but failed to reach significance ($F_{1,13}$ = 2.45, p = .14, f = 0.43). All other effects were non-significant and had small to moderate effect sizes (*F*s < 1.50, *p*s > .24, *f*s < 0.34). The significant effect of test showed that performance of the HPT was systematically better (*M* = 5.28, *SD* = 1.82) than that of the LPT (*M* = 4.63, *SD* = 1.63). A separate Group (EG, AG) × Session (S1, S6) × Test (LPT, HPT) ANOVA for movement execution resulted in a significant effect of group ($F_{1,13}$ = 5.30, p < .05, f = 0.64), with the EG performing better on average (*M* = 2.72, *SD* = 0.45) than the AG (*M* = 2.21, *SD* = 0.45), again a result that was also already visible during acquisition. All other effects were non-significant (*F*s < 1.58, *p*s > .23, *f*s < 0.35). A Group (EG, AG) × Session (S1, S6) × Test (LPT, HPT) ANOVA on the accuracy scores revealed significant effects of session ($F_{1,13}$ = 5.52, p < .05, f = 0.65) and test ($F_{1,13}$ = 31.00, p < .001, f = 1.53), in the absence of any significant interactions (*F*s < 1.51, *p*s > .24, *f*s < 0.34). The effect of group had a large effect size (f = 0.47), but did not reach significance ($F_{1,13}$ = 2.88, p < .11). It appears that S6 was performed more accurately (*M* = 2.13, *SD* = 0.32) than S1 (*M* = 1.87, *SD* = 0.48), the HPT was performed more accurately (*M* = 2.16, *SD* = 0.42) than the LPT (*M* = 1.84, *SD* = 0.40). Thus, the increase in performance scores from LPT to HPT was primarily the result of an increase in accuracy. Most important, performance was not negatively affected by the (successful) pressure manipulations. This was the case for both groups after already 1,400 repetitions, despite clear differences in the number of explicit rules.

Discussion

The aim of the present study was to investigate explicit and analogy learning over substantially more repetitions (i.e., 10,000) than were previously considered in similar learning studies (i.e., up to 500). Specifically, we sought to test the effects of explicit and analogy learning on performance under pressure in relation to the number of explicit rules available for movement control when performance had been automatized in both learning groups, that is, when their performance could sustain the additional workload of a secondary task (i.e., the standard method for investigating automaticity, Passingham, 1996). We found that the number of explicit rules decreased from 1,400 to 10,000 repetitions in the explicit learners, but remained low and relatively constant in the analogy learners. Note that after 10,000 trials explicit learners reported 4.78 internal explicit rules – a number that may still be considered a fair indication of explicit learning, and sufficient to cause choking under pressure (Hardy et al., 1996; Koedijker et al., 2007; Liao & Masters, 2001; Masters, 1992).

The fact that performance of both analogy and explicit learners seemed to be robust to secondary task loading after 1,400 and 10,000 repetitions suggested that both learning groups had already reached some degree of automaticity after 1,400 repetitions. We ought to be careful with this conclusion as it is based on the absence of significant differences between the low pressure and dual-task tests with a relatively low sample size.[1] Nevertheless, in previous studies using the same primary and secondary tasks and comparable sample sizes (Koedijker et al., 2007, Liao & Masters, 2001) performance of explicit learners was harmed by the secondary task after approximately 500 repetitions. Furthermore, the conclusion that some degree of automaticity was achieved after 1,400 repetitions would be consistent with Bernstein's (1996) idea that automaticity is a relatively early (rather than the last) step in achieving expertise, which is followed by time-consuming processes of standardization and stabilization after many more repetitions. Interestingly, after 1,400 repetitions the accumulated number of explicit rules reported by the explicit learners did not lead to performance degradation under pressure. This unexpected result can neither be explained by a lack of statistical power (because significant increases, rather than decreases, were found), nor by a failure of our pressure manipulation (because anxiety scores increased significantly from low to high pressure conditions). Apparently, anxiety did affect performance, albeit no longer in the expected direction, at least not in the explicit learning group. In combination these results do not support the reinvestment hypothesis, because despite a relatively high number of explicit rules performance of explicit learners did not decrease with anxiety. This result stands in contrast to studies with lower numbers of repetitions.

To place this finding in the right perspective and before discussing its theoretical implications, it is important to address several limitations of the current study. First, previous studies involving maximally 500 repetitions have demonstrated a relation between the number of internal, explicit rules and performance under pressure or under secondary task loading (Koedijker et al., 2007; Liao & Masters, 2001, Masters 1992; Poolton et al., 2005, Poolton, Maxwell, et al., 2006). Admittedly, for a fair comparison it would have been better in hindsight if we would have included test measurements after 500 trials as well. However, we had not anticipated that the alleged effect of performance degradation would already wash out between 500 and 1,400 trials. In addition, for practical reasons related to having participants hit as many as 10,000 balls, we decided not to include test measurements at 500 trials, also because comparable test measurements after 500 trials were available from a previous study (Koedijker et al., 2007). In that study, we conducted a similar experiment, albeit with considerably less repetitions. We examined the same task, the table tennis forehand, using the exact same instructions in a sample of participants gathered from the same student population as the participants from the present study. Importantly, if we insert the performance scores after 500 trials (Koedijker et al., 2007) in the performance scores of the present study, they fit in well with the learning curve, which gives confidence in the reliability of the findings and their comparison across experiments.

Second, the specific nature of the task (fast and externally-paced) urges us to be careful in generalizing our findings to other task domains. The time taken to execute 10,000 table tennis repetitions will be different from the time taken to perform the same number of repetitions in self-paced and slower tasks such as golf-putting or free throw shooting which will affect the generalizability of our findings. Nevertheless, no study to date tested the reinvestment hypothesis with such a large number of repetitions (i.e., 20 times more repetitions than in previous studies, including two studies investigating the table tennis forehand; Koedijker et al., 2007; Liao & Masters, 2001) hereby significantly extending the learning phase investigated. Furthermore, the task investigated and the accompanying time invested in learning the task under a specific set of repetitions are comparable with the two table-tennis forehand studies investigating up to 500 repetitions (Koedijker et al., 2007; Liao & Masters, 2001), which lends confidence to our conclusion regarding the reinvestment hypothesis. Needless to say, further work is needed to disambiguate the influence of time spent in practice (number of hours, cf. Ericsson, 1996) and the number of repetitions on skill learning in tasks of varying nature.

Third, there was one important difference between the present study and the two previous studies (Koedijker et al., 2007; Liao & Masters, 2001). Here, we employed a ball feed frequency of 50 balls per minute, whereas Koedijker et al. (2007) and Liao and Masters (2001) employed a frequency of 25 balls per minute in both learning and performance conditions. In general, one could question to what degree the nature of the task (rapid and externally paced) may have affected the likelihood of rule use (i.e., hypothesis testing) during learning, opening up the possibility that the present explicit learning group learned implicitly rather than explicitly. However, this should have been reflected in a lower number of reported explicit rules, which was not the case. Furthermore, rule testing behavior could be initiated in the one-minute breaks between sets of 100 balls so that specific explicit rules were tested from set to set rather than trial to trial. Finally, close inspection of the video footage revealed frequent changes in movement execution even within the blocks of 100 repetitions, which may provide an indication of hypothesis-testing behavior.

All in all, it seems reasonable to conclude that with the current task performance of explicit learners was hampered with comparable levels of anxiety or a second task after about 500 repetitions, while this was no longer the case after 1,400 or 10,000 trials, despite the presence of explicit rules. Thus, it seems that already between 500 and 1,400 repetitions explicit learners shifted control of its carrying features from a conscious to a subconscious level, despite the availability of a relatively high number of explicit rules. Such a shift would result in an increase in available working memory resources that may be absorbed by processes involving anxiety without harming performance in a similar fashion as in implicit learners after already a very small number (< 500) of repetitions. Future studies are necessary to determine whether these findings generalize to other tasks, including slower and self-paced tasks, such as golf putting.

As for the theoretical implications, our finding that choking under pressure is not uniquely related to the number of explicit rules after a sufficient number of repetitions during learning, lends indirect support to the processing efficiency theory (Eysenck & Calvo, 1992; recently evolved into attentional control theory, Eysenck, Derakshan, Santos, & Calvo, 2007) as this theory provides an alternative explanation for choking. The basic premise of the processing efficiency theory concerning the adverse effects of anxiety on performance originates from distraction models proposing that anxiety shifts attention away from task-relevant information to task-irrelevant cues, thereby decreasing performance (e.g., Wine, 1971; see also Beilock & Carr, 2001; Lewis & Linder, 1997; Mullen & Hardy, 2000). It is assumed that the debilitating effects of performance pressure are the result of anxiety-induced increases in self-consciousness involving self-reflection and more attention to, for instance, worries about performance (Baumeister, 1984; Carver & Scheier, 1978; Lewis & Linder, 1997; Mor & Winquist, 2002; Wegner & Giuliano, 1980), rather than increased attention to movement control, that is, reinvestment. Although processing efficiency theory was originally claimed to be most relevant for cognitive task performance (Eysenck & Calvo, 1992), several recent studies have generated empirical support for the theory with respect to perceptual-motor tasks (Mullen & Hardy, 2000; Mullen, Hardy, & Tattersall, 2005; Murray & Janelle, 2003, 2007; Smith, Bellamy, Collins, & Newell, 2001; Williams, Vickers, & Rodrigues, 2002; Wilson, Smith, Chattington, Ford, & Marple-Horvat, 2006).

Moreover, according to the processing efficiency theory anxiety does not necessarily have to lead to a decrement in performance as was found in the present study and several earlier studies (Hardy, Beattie, & Woodman, 2007, Hardy & Parfitt, 1991; Hardy, Parfitt, & Pates, 1994). The theory proposes that the adverse effects of anxiety may be compensated for by processes involving increased on-task effort and activities aimed at performance improvement. In this case processing efficiency of task execution – that is, performance effectiveness divided by effort – may be impaired while performance effectiveness itself, and thus task performance remains unharmed or even improves.

Finally, we found that performance continued to improve after 1,400 repetitions in the explicit learning group, but leveled off in the analogy learning group. A closer inspection of the data revealed that this advantage of explicit over analogy learning primarily resided in an increase in movement execution rather than accuracy. In analogy learning, only one rule is provided and if movement execution is suboptimal, it is difficult to improve performance without having the possibility to test new movement-related hypotheses or without additional information about movement execution. In explicit learning such explicit processes may serve as an error-detection-and-correction mechanism that facilitates further improvement on suboptimal skill execution, as one may continue to test hypotheses about movement execution even over a longer period (Baddeley & Wilson, 1994; Jacoby, Baker, & Brooks, 1989). When using an analogy the possibility to learn from detecting and correcting errors is limited as there is only one rule that can be used for this purpose (Baddeley & Wilson, 1994; cf. Maxwell et al., 2000). As a result, analogy learning progression may quickly asymptote if no measures are taken to further improve performance, for instance, by providing performance feedback (i.e., score) to enhance motivation, or to increase the difficulty of the task to make it more challenging. Admittedly, such measures would probably also enhance explicit learning performance. Alternatively, a new analogy or a change to the analogy may be introduced. Whether these suggestions may indeed lead to further improvements (comparable to the progression made with explicit learning) should be tested in future research. For now, the present findings provide little ground for attempting to withhold learners from accumulating knowledge in the course of learning in view of its potentially detrimental effects on performance. After all, if the number of reported explicit rules is not related to performance under pressure, there is no need for learners to be discouraged to accrue information that might help them improve their performance.

References

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89,* 369-406.

Baddeley, A., & Wilson, B. A. (1994). When implicit learning fails: Amnesia and the problem of error elimination. *Neuropsychologia, 32*, 53-68.

Bakker, F. C., Vanden Auweele, Y., & van Mele, V. (2003). *Competitie-Belevings-Vragenlijst (ICBV) en Vragenlijst Beleving voor een Sportwedstrijd (VBS)*. Leuven: Acco.

Baumeister, R. F. (1984). Choking under pressure: Self-consciousness and paradoxical effects on incentives on skillful performance. *Journal of Personality and Social Psychology, 46*, 610-620.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General, 130*, 701-725.

Beilock, S.L., & Carr, T.H. (2005). When high-powered people fail: Working memory and "choking under pressure" in math. *Psychological Science, 16,* 101-105.

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *Journal of Experimental Psychology: Applied, 8,* 6-16.

Bennett, S. J. (2000). Implicit learning: Should it be used in practice? *International Journal of Sport Psychology, 31*, 542-546.

Bernstein, N. (1967). *The coordination and regulation of movements*. New York, NY: Pergamon.

Carver, C. S., & Scheier, M. F. (1978). Self-focusing effects of dispositional self-consciousness, mirror presence, and audience presence. *Journal of Personality and Social Psychology, 36,* 324-332.

Carver, C. S., & Scheier, M. F. (2000). *Perspectives on personality* (4th ed.). Boston, Mass.: Allyn & Bacon.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2 ed.). Hillsdale, NJ: Erlbaum.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics, 2*, 153-166.

Ericsson, K. A. (1996). The acquisition of expert performance: An introduction to some of the issues. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in arts and sciences, sports, and games* (p. 1-50). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Ericsson, K., Krampe, R. & Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100,* 363-406.

Eysenck, M. W., & Calvo, M. G. (1992). Anxiety and performance: The processing efficiency theory. *Cognition and Emotion, 6*, 409-434.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*, 336-353.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods,* 175-191.

Fenigstein, A, Scheier, M. F., & Buss, A. H. (1975). Public and private self-consciousness: Assessment and theory. *Journal of Consulting and Clinical Psychology, 43*, 522-527.

Fitts, P., & Posner, M. (1967). *Human performance*. Belmont, CA: Brooks-Cole.

Girden, E. R. (1992). ANOVA: Repeated measures. Newbury Park: Sage

Hardy, L, Beattie, S., & Woodman, T. (2007). Anxiety-induced performance catastrophes: Investigating effort required as an asymmetry factor. *British Journal of Psychology, 98*, 15-31.

Hardy, L., Mullen, R., & Jones, G. (1996). Knowledge and conscious control of motor actions under stress. *British Journal of Psychology, 87*, 621-636.

Hardy, L., & Parfitt, C. G. (1991). A catastrophe model of anxiety and performance. *British Journal of Psychology, 82*, 163-178.

Hardy, L., & Parfitt, C. G., & Pates J. (1994). Performance catastrophes in sport: A test of the hysteresis hypothesis. *Journal of Sport Sciences. 12*, 327-334.

Hodges, L. (1993). *Table tennis: Steps to success.* Campaign, IL: Human Kinetics.

Hodges, N. J., & Starkes, N. J. (1996). Wrestling with the nature of expertise: A sport specific test of Ericsson, Krampe & Tesch-Römer's (1993) theory of 'deliberate practice'. *International Journal of Sport Psychology, 27*, 400-424.

Houtman, I. L. D., & Bakker, F. C. (1989). The anxiety thermometer: A validation study. *Journal of Personality Assessment, 53*, 575-582.

Howell, D.C. (2007) *Statistical Methods for Psychology*. Belmont, Thomson Wadsworth.

Hughes, M., & Franks, I. M. (2004). *Notational analysis of sport: Systems for better coaching and performance in sport (2nd edition)*. London: Routledge.

Jacoby, L. L., Baker, J. G., & Brooks, L. R. (1989). Episodic effects on picture identification: Implications for theories of concept learning and theories of memory. *Journal of Experimental Psychology: Learning, Memory, Cognition*, *15*, 275-281.

Koedijker, J. M., Oudejans, R. R. D., & Beek, P. J. (2007). Explicit rules and direction of attention in learning and performing the table tennis forehand. *International Journal of Sport Psychology, 38*, 227-244.

Kottke, F. J. (1980). From reflex to skill: The training of coordination. *Archives of Physical Medicine and Rehabilitation, 61*, 551-561.

Lewis, B. P., & Linder, D. E. (1997). Thinking about choking? Attentional processes and paradoxical performance. *Personality and Social Psychology Bulletin, 23*, 937-944.

Liao, C.-H., & Masters, R. S. W. (2001). Analogy learning: A means to implicit motor learning. *Journal of Sports Sciences, 19,* 307-319.

MacMahon, K. M. A., & Masters, R. S. W. (2002). The effects of secondary tasks on implicit motor skill performance. *International Journal of Sport Psychology, 33,* 307-324.

Martens, K., Vealy, R. S., & Burton, D. (1990). *Competitive anxiety in sport.* Champaign, IL: Human Kinetics.

Masters, R. S. W. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology, 83*, 343-358.

Masters, R. S. W., & Maxwell, J. P. (2004). Implicit motor learning, reinvestment and movement disruption. What you don't know won't hurt you? In A. M. Williams & N. J. Hodges (Eds.), *Skill acquisition in sport: Research, theory and practice* (pp. 207-228). London: Routledge.

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2000). From novice to no know-how: A longitudinal study of implicit motor learning. *Journal of Sports Sciences, 18*, 111-120.

Maxwell, J. P., Masters, R. S. W., Kerr, E., & Weedon, E. (2001). The implicit benefit of learning without errors. *The Quarterly Journal of Experimental Psychology, 54A*, 1049-1068.

Mor, N., & Winquist, J. (2002). Self-focused attention and negative affect: A meta-analysis. *Psychological Bulletin, 128*, 638-662.

Mullen, R., & Hardy, L. (2000). State anxiety and motor performance: Testing the conscious processing hypothesis. *Journal of Sports Sciences, 18*, 785-799.

Mullen, R., Hardy, L., & Tattersall, A. (2005). The effects of anxiety on motor performance: A test of the conscious processing hypothesis. *Journal of Sport & Exercise Psychology, 27*, 212-225.

Murray, N. P., & Janelle, C. M. (2003). Anxiety and performance: A visual search examination of the processing efficiency theory. *Journal of Sport & Exercise Psychology, 25*, 171-187.

Murray, N. P., & Janelle, C. M. (2007). Event-related potential evidence for the processing efficiency theory. *Journal of Sports Science, 25,* 161-171.

Passingham, R. E. (1996). Attention to action. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 1473-1479.

Pijpers, J. R., Oudejans, R. R. D., Bakker, F. C., & Beek, P. J. (2006). The role of anxiety in perceiving and realizing affordances. *Ecological Psychology, 18,* 131-161.

Poolton, J. M., Masters, R. S.W., & Maxwell, J. P. (2005). The relationship between initial errorless learning conditions and subsequent performance. *Human Movement Science, 24,* 362-378.

Poolton, J. M., Masters, R. S. W., & Maxwell, J. P. (2007). Passing thoughts on the evolutionary stability of implicit motor behaviour: Performance retention under physiological fatigue. *Consciousness & Cognition, 16,* 456-468.

Poolton, J. M., Maxwell, J. P., Masters, R. S. W., & Raab, M. (2006). Benefits of an external focus of attention: Common coding or conscious processing? *Journal of Sports Sciences, 24,* 89-99.

Smith, N. C., Bellamy, M., Collins, D. J., & Newell, D. (2001). A test of processing efficiency theory in a team sport context. *Journal of Sports Sciences, 19,* 321-332.

Starkes, J. L. (2000). The road to expertise: Is practice the only determinant? *International Journal of Sport Psychology, 31*, 431-451.

Wegner, D. M., & Giuliano, T. (1980). Arousal-induced attention to self. *Journal of Personality and Social Psychology, 38,* 719-726.

Williams, A. M., Vickers, J., & Rodrigues, S. (2002). The effects of anxiety on visual search, movement kinematics, and performance in table tennis: A test of Eysenck and Calvo's processing efficiency theory. *Journal of Sport & Exercise Psychology, 24,* 438-455.

Willingham, D. B., & Goedert-Eschmann, K. (1999). The relation between implicit and explicit learning: Evidence for parallel development. *Psychological Science, 10,* 531-534.

Wilson, M., Smith, N. C., Chattington, M., Ford, M., & Marple-Horvat, D. E. (2006). The role of effort in moderating the anxiety-performance relationship: Testing the prediction of processing efficiency theory in simulated rally driving. *Journal of Sports Sciences*, *24*, 1223-1233.

Wine, J. (1971). Text anxiety and direction of attention. *Psychological Bulletin, 76,* 92-104.