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The implicit benefit of learning without errors

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Two studies examined whether the number of errors made in learning a motor skill, golf putting, differentially influences the adoption of a selective (explicit) or unselective (implicit) learning mode. Errorful learners were expected to adopt an explicit, hypothesis-testing strategy to correct errors during learning, thereby accruing a pool of verbalizable rules and exhibiting performance breakdown under dual-task conditions, characteristic of a selective mode of learning. Reducing errors during learning was predicted to minimize the involvement of explicit hypothesis testing leading to the adoption of an unselective mode of learning, distinguished by few verbalizable rules and robust performance under secondary task loading. Both studies supported these predictions. The golf putting performance of errorless learners in both studies was unaffected by the imposition of a secondary task load, whereas the performance of errorful learners deteriorated. Reducing errors during learning limited the number of error-correcting hypotheses tested by the learner, thereby reducing the contribution of explicit processing to skill acquisition. It was concluded that the reduction of errors during learning encourages the use of implicit, unselective learning processes, which confer insusceptibility to performance breakdown under distraction.

Traditional theories postulate that motor skills are initially acquired explicitly via cognitive processing which is verbally based. As learning proceeds, the skill becomes automated or implicit. That is, the verbal rules used to perform the skill are “forgotten”, and task-relevant information processing becomes unconscious (Anderson, 1983; Fitts & Posner, 1967). The initial stages of learning are characterized by conscious processing of task-relevant information via a hypothesis-testing strategy. The performer makes intuitive judgements about how best to perform the task and selects successful attempts for future performance, avoiding unsuccessful attempts. This process leads to a relatively small knowledge base that can be explicated and, hence, is explicit. Berry and Broadbent (1988) described this process as selective or S-mode learning, which is analogous to explicit learning.

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Recent research on the implicit acquisition of motor skills challenges the assumption that the acquisition of motor skills necessarily proceeds from explicit to implicit. Implicit learning involves the acquisition of a skill without a corresponding increase in verbal knowledge about the skill (Masters, 1992). The performer is, typically, unable to test hypotheses or identify crucial aspects of skilled performance. Instead, they passively aggregate all task-relevant information or action-outcome contingencies. This passive aggregation of task-relevant information leads to a large knowledge base that is not easily verbalized. Performance is supported by a gradual increase in successful action–outcome contingencies. This process is analogous to what Berry and Broadbent (1988) described as unselective or U-mode learning.

Hayes and Broadbent (1988) further refined the S-mode/U-mode distinction, by showing that S-mode learning utilizes abstract working memory (Broadbent, 1984), whereas U-mode does not. Using a complex interactive task, Hayes and Broadbent demonstrated that a concurrent random letter generation task (Baddeley, 1966), which loads abstract working memory, increased decision times for S-mode learners but reduced the time taken by subjects utilizing U-mode. The secondary task load was also found to interfere with the learning of an unexpected reversal in the relationship between the S-mode learner's input and the system's output. Hayes and Broadbent interpreted these findings as support for their abstract working-memory hypothesis. A number of recent studies using sequence-learning tasks (Cohen, Ivry, & Keele, 1990; Frensch, Wenke, & Rünger, 1999; Jiménez & Méndez, 1999), conceptual priming (Mulligan, 1997), and word stem completions (Wolters & Prinsen, 1997) support the proposal that implicit processes are not attentionally demanding, whereas explicit processes are attentionally demanding. Consequently, robust performance under a secondary task load appears to be a relatively reliable test for the existence of implicit processing and has been proposed as a dissociating characteristic (Berry & Dienes, 1993).

A number of previous studies, which have used a golf putting task to examine implicit motor learning, have adopted a dual-task methodology to facilitate implicit learning. Masters (1992) had subjects learn a complex motor skill, golf putting, whilst performing a secondary task. The secondary task, random letter generation (Baddeley, 1966), was hypothesized to prevent the acquisition of explicit knowledge. Implicit learners were shown to accrue little verbalizable, explicit knowledge of the putting skill when compared to explicit learners who performed the putting task only. Additionally, the putting performance of the implicit group improved over trials, demonstrating that learning had occurred. In demonstrating learning without accumulation of explicit knowledge, Masters concluded that subjects had acquired the motor skill implicitly. Additionally, Masters (1992) demonstrated that the performance of the implicit group improved under psychological stress relative to the performance decrement of the explicit group. Robust performance under psychological stress is another proposed characteristic of implicit processes (Reber, 1989, 1993).

These findings were later replicated by Hardy, Mullen, and Jones (1996), supporting Masters' (1992) results. Hardy et al. initially argued that the increased performance level of the implicit group during the stress phase might have been due to release from the secondary task load. To test this explanation they had two implicit groups learn the golf putting task whilst performing the random letter generation task. During the stress phase one implicit group performed the putting task only while the other group continued performing the secondary task. Hardy et al. reasoned that the former group would show the normal increase in performance during the stress phase but the latter group would not, indicating that release from the secondary task load was responsible for Masters' increased performance levels during the stress phase. Despite their predictions the performance level of both groups improved during the stress phase, lending support to Masters' implicit learning hypothesis.

A recent study that replicates but does not cite the work of Hardy et al. (1996), (Bright & Freedman, 1998), again found increased performance under stress for a group liberated from secondary task loading. However, it found that the group who continued to perform the secondary task during the stress phase did not improve, contrary to the Hardy et al. findings. Bright and Freedman concluded that the increase in performance under stress seen in Masters' (1992) implicit group was due to release from the secondary task load and not to robustness conferred by the implicit nature of their knowledge. Unfortunately, the protocol employed by Bright and Freedman had important failings, which undermined their conclusions. First, they failed to use novice subjects, a criterion Masters stressed as essential. Participants in the Bright and Freedman study are likely to have brought explicit knowledge to the experiment, preventing any comparison with novice participants in the previous studies. Second, participants performed only 160 trials during the learning phase compared with 400 in the Masters and Hardy et al. studies. The amount of practice during learning is likely to affect the expression of explicit and implicit processing, again precluding comparisons between the Bright and Freedman study and the studies of Masters and Hardy et al.

In all of the studies discussed the performance levels of subjects learning the golf putting task while performing the concurrent secondary task have consistently been below those of subjects performing the putting task alone (Bright & Freedman, 1998; Hardy et al., 1996; Masters, 1992). This remained true even after an extended number of practice trials ($n = 3000$: Maxwell, Masters, & Eves, 2000). Clearly, a practical alternative to the dual-task paradigm needs to be established.

A possible solution to the performance problem may come from a suggestion by Baddeley and Wilson (1994). They proposed that explicit processes function by identifying and eliminating errors during learning, whereas implicit processes encode frequency information and are unable to correct errors, accounting for the poor performance of implicit learners. Implicit learners in the golf putting studies may learn via an unselective mode that involves the aggregation of all action–outcome links regardless of their success. The knowledge base that supports the performance of implicit learners is comprised of both successful and unsuccessful actions. Explicit or S-mode learners are able to identify and avoid errorful actions, thus their performance is supported by a relatively error-free knowledge base. The performance of implicit learners may be poorer simply because they are unable to avoid the repetition of errors (Baddeley, 1992; Baddeley & Wilson, 1994).

Numerous studies have demonstrated that providing guidance or prompting during learning leads to better performance than does trial-and-error-learning (Holding, 1970; Hunkin, Squires, Parkin, & Tidy, 1998; Prather, 1971; Robinson & Storm, 1978; Singer, 1977; Wulf, Shea, & Whitacre, 1998), although in the majority of these studies performance during delayed retention and transfer tests was poorer. It is important to note, however, that in these studies errorless learners have performed the retention and transfer tests without the guidance received during learning. For example, Wulf et al. (1998) had participants learn a slalom ski-simulator task with the help of ski poles. During subsequent retention tests, these poles were removed, crucially altering the requirements of the task and thereby reducing performance level. The conditions used in the following experiments do not change from learning to retention; therefore, the high performance level exhibited by errorless learners during acquisition is more likely to be maintained during retention.

Prather (1971) observed that subjects learning under errorless conditions appeared to acquire the skill in a passive manner, which is similar to implicit or U-mode learning. Persons learning under trial-and-error conditions seemed actively to test hypotheses, similar to explicit or S-mode learning. It is possible that when errors are present the performer has to create hypotheses about how to correct them and, thus, adopts a selective learning strategy. When errors are absent, there is no need to test hypotheses because the movement is effective (successful). Therefore, participants who do not make errors may adopt an unselective mode of learning by default.

EXPERIMENT 1

Experiment 1 was designed to test the possibility that errorless learners will adopt a passive, U-mode learning strategy, whereas errorful learners will adopt an active, S-mode learning strategy. Rather than physically guide performers, the difficulty of a golf putting task was manipulated such that errors would occur at differential rates during learning. Errorless learners started putting near to the hole and gradually putted from progressively greater distances, whereas errorful learners started putting 2m from the hole and moved progressively closer. Two measures were used to test the implicit status of participants' knowledge: Verbal protocols and secondary task loading. Errorless learners were hypothesized to accrue few verbalizable rules during learning and to demonstrate robust performance under secondary task loading. Errorful learners, however, were predicted to accrue a large pool of explicit rules during learning and suffer from performance breakdown under secondary task loading. A third group that putted from random distances during learning was included in the design to control for the effect of putting order on subsequent performance. It was predicted that this group would make a large number of mistakes, invoking a hypothesis-testing strategy, and would demonstrate characteristics compatible with a selective mode of learning.

Performance characteristics during learning and retention remain comparable because errors were manipulated without providing supplemental guidance. In both phases, the performers controlled movement production with no external guidance. Contrary to the findings of previous studies, where conditions have been changed during retention, we predicted that persons who make fewer errors during learning would continue to make fewer errors during retention under unchanged conditions. In addition, previous studies utilizing simpler tasks than the one used here (Macrae & Holding, 1965a, b; Prather, 1971; see Wulf et al., 1998 for an exception) have demonstrated poor transfer to novel situations. Therefore, a novel distance transfer test was employed to test the possibility that poor transfer is a common feature of errorless learning, independent of task complexity.

Method

Participants

A total of 36 undergraduate sport science students participated as part of a course requirement. Participants were required to have no previous golfing experience, and 7 participants who failed to meet this criterion were subsequently dropped from the study. The remaining participants were randomly assigned to one of three conditions; errorless ($n = 11$), errorful ($n = 9$) and random ($n = 9$). Ages ranged from 20 to 33 years ($M = 20.86$, $SD = 2.4$).

Apparatus

All subjects used a standard golf putter, 89 cm in length, and standard white golf balls. Putts were made to a hole 11.5 cm in diameter from varying distances. The surface was artificial grass (County Turf, En-Tout-Cas) raised 14 cm above ground level to allow a collecting duct to be fit beneath the hole. The surface was even and level. A Dell 486P/33 computer generated tones for the secondary task condition.

Procedure

The study was divided into two phases, learning and test. The learning phase consisted of eight blocks of 50 trials performed from eight distances (25, 50, 75, 100, 125, 150, 175, and 200 cm). The errorless group performed the first block from the shortest distance and then moved back through each distance until they reached the furthest distance on the final block. The errorful group began putting from the furthest distance and moved progressively closer until the last block, which was performed at the shortest distance from the hole. The random group also performed at each distance but in a pseudo-random order (125, 25, 100, 150, 75, 200, 50, and 175 cm). The random group was expected to perform at a level comparable with that of the errorful group and in a qualitatively similar way. At the end of the learning phase, all participants completed verbal protocols describing any "rules, knowledge, or methods" that they had used or become aware of using during practice.

The test phase consisted of three blocks of 50 trials, consisting of a 200-cm retention test, a 200-cm secondary task transfer test, and a novel distance (300 cm) transfer test. During the retention test, participants were asked to hole as many balls as possible. During the secondary task transfer test, participants were required to hole as many balls as possible while performing a secondary task. The task required participants to monitor and subsequently report the number of high-pitched tones in a random array of high- and low-pitched tones presented at a rate of one per 1500 ms. The novel distance transfer test required subjects to again hole as many balls as possible, but from a distance of 300 cm.

It is normal procedure within the motor learning literature to employ a pre-test of ability to ensure that all groups are matched prior to learning and to allow an assessment of the extent of subsequent learning (Magill, 1993). For two reasons, it was not possible to use this procedure here. First, the three groups began putting from different distances during the initial learning period; thus, their respective performances are not directly comparable. Second, the use of a pre-test would incur two problems. Putting from the shorter distances of 100 cm and below introduces a ceiling effect to the performance measure because all participants perform at near-perfect levels. Putting from longer distances introduces errors into the performance of the errorless group, invalidating their errorless standing and perhaps introducing explicit qualities to their knowledge base. This would invalidate verbal protocol data and bring into question the errorless group's implicit status. For these reasons, we assumed that all groups were matched for ability (due to the random group allocation procedure), and we utilized the performance of the errorful group during the first block of trials as an approximate indication of baseline performance prior to learning, although group differences may have been encountered and cannot be discounted.

Results

Orthogonal contrasts are used to analyse specific, a priori predictions throughout the Results section in addition to the more traditional one-way analyses of variance, which preclude the use of a priori predictions. The specific predictions are detailed in their respective sections.

Learning phase

During the learning phase, the errorless group was predicted to make fewer errors than the errorful and random groups combined. The errorful and random groups were predicted to make a similar number of errors during this phase. Orthogonal contrasts were used to test these specific predictions. The number of errors made by the errorless group during the learning phase differed significantly from the other two groups, $t(26) = 3.175$, $p = .004$. The number of errors made by the errorful and random groups did not differ, $t(26) = -1.693$, $p = .102$. The errorless group made fewer errors than the errorful and random groups during learning, indicating that this group had learnt in a relatively errorless fashion (Figure 1).

The mean number of successful putts made by the errorful group during the first block of practice was 22.0 ($SD = 4.92$). All three groups appear to have performed at a higher level during the retention test, suggesting that learning had taken place (Figure 2). A one-way analysis of variance (ANOVA) comparing the score of the errorful group during Block 1 with the scores of all three groups during retention was utilized to establish evidence of learning. A significant effect of group, $F(3, 37) = 22.079$, $p < .001$, was found. Newman–Keuls' a posteriori test indicated that all three groups performed at a higher level during retention than did the errorful group during Block 1, supporting the contention that all three groups improved during the learning phase.

In addition to the orthogonal contrasts, a more traditional Group × Block (3 × 8) ANOVA with repeated measures on the latter factor was computed. Greenhouse–Geisser epsilon adjusted probabilities are reported for all statistical tests involving the repeated measure. Highly significant main effects of group, $F(2, 26) = 6.472$, $p = .005$, and block, $F(7, 182) = 78.84$, $p < .001$, were found. The interaction was also highly significant, $F(14, 182) = 4.646$, $p < .001$. Newman–Keuls a posteriori test showed significant differences between groups at the four longest distances only; the errorless group successfully holed more balls at these distances than did the other two groups except at the 175-cm distance. At this distance, the random group did not differ from the errorless group. The confound between learning and putting distance makes both the block effect and interaction difficult to interpret. All three groups perform worse at the longer distances ($p < .05$), which accounts for the effect of block.

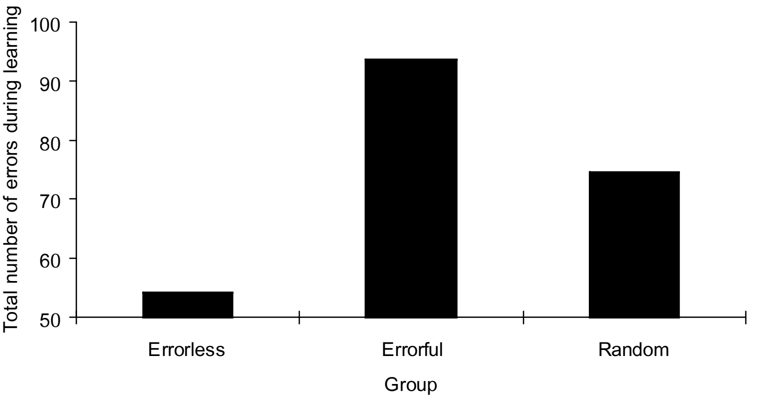

Figure 1. Mean total number of errors made by the errorless, errorful, and random groups during the learning phase.

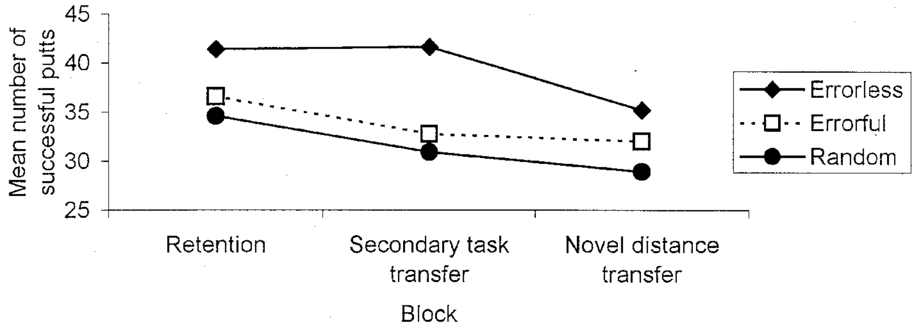

Figure 2. Mean number of successful putts made during the test phase.

The errorless group's superior performance relative to the other groups at the longer distances accounts for the interaction. These findings are consistent with those expected due to the differing order in which each group experienced the various putting distances and provide further support for the contention that errorless learning results in better performance.

Retention test

It was predicted that, consistent with performance during the learning phase, the errorless group would continue to perform at a higher level during the retention test than would the other two groups, who would not differ from each other. Orthogonal contrasts, with number of successful putts as the dependent measure, demonstrated that the level of performance of the errorless group was significantly higher than that of the other two groups, $t(26) = 2.721$, $p = .01$, who did not differ from each other, $t(26) = 0.761$, $p = .45$. Mean (*SD*) number of successful putts was 41.36 (6.61), 36.56 (4.75), and 34.56 (4.90) for the errorless, errorful and random groups, respectively. This is shown in Figure 2.

Secondary task transfer test

The errorless group was predicted to learn in a passive manner, utilizing U-mode, which would be demonstrated by robust performance under the imposition of a secondary task load. The errorful and random groups, however, were hypothesized to acquire the putting skill via S-mode and suffer a breakdown in performance under dual-task loading. A Group × Block (3 × 2) ANOVA with repeated measures on the block factor produced highly significant effects of group, $F(2, 26) = 7.01$, $p = .004$, and block, $F(1, 26) = 10.37$, $p = .003$. A significant interaction was also found, $F(2, 26) = 3.44$, $p = .047$. Post hoc analysis revealed that the errorless group performed at a higher level than did the other two groups during the retention and secondary task transfer test. The performance of the errorless group did not deteriorate over blocks ($p > .05$), whereas the performance of the other two groups significantly declined ($p < .05$).

Orthogonal contrasts were utilized to test the specific prediction that the random and errorful groups would demonstrate a larger deterioration in performance under secondary task loading than would the errorless group, with change in score from retention test to secondary task transfer test as the dependent measure. They showed that the change in score of the errorless group differed significantly from the change in score of the other two groups, $t(26) = 2.62$, $p = .01$. The changes in score of the errorful and random groups did not differ, $t(26) = -0.06$, $p = .95$. The errorless group's performance was unaffected by the imposition of a secondary task load, whereas, the performance of the other two groups degraded relative to that of the errorless group (Figure 2). Mean (*SD*) number of successful putts was 41.64 (6.67), 32.78 (5.89), and 30.89 (5.93) for the errorless, errorful, and random groups, respectively.

To ensure that all groups performed the tone-counting task equally well a one way ANOVA, with absolute percentage accuracy as the dependent measure, was carried out. No significant differences were found between groups, $F(2, 28) = 1.31$, $p = .29$; mean (*SD*) tone-counting accuracy was 93.27% (8.77), 94.88% (6.89), and 98.14% (2.29) for the errorless, errorful, and random groups, respectively. Calculation of Pearson's product–moment correlation coefficient demonstrated no relationship between tone-counting accuracy and change in performance under secondary task load ($r = .135$, $n = 29$, $p = .486$). Therefore, differing allocation of attentional resources to the primary and secondary tasks does not account for the performance differences reported here.

Novel distance transfer test

The errorless group were predicted to continue performing at a higher level than the other groups, who would perform at comparable levels to each other, during the novel distance transfer test. Orthogonal contrasts taking number of balls successfully holed as the dependent measure indicated that the errorful and random groups performed at a similar level, $t(26) = 1.26$, $p = .22$, and the errorless group's score was significantly different from that of these two groups, $t(26) = 2.36$, $p = .026$. The errorless group holed more balls when transferred to a novel distance than did the other two groups (Figure 2). Mean (*SD*) number of successful putts was 35.18 (4.14), 32.00 (4.97), and 28.89 (6.58) for the errorless, errorful, and random groups, respectively.

However, the higher performance of the errorless group can be explained by their higher performance level overall. Therefore, the analysis was repeated with change in score from retention test to novel distance transfer test as the dependent measure. No differences between groups were found ($p > .05$), suggesting that change in score as a result of transfer to the novel distance was comparable for all three groups (see Figure 2).

Verbal protocols

Two independent raters assessed the number of rules reported by each subject. The raters were blind to the experimental condition under which each participant performed. Statements made by participants were counted as rules if they specifically described aspects of the performer's technique that might have been used during learning (e.g., "I held my left hand above my right" or "My feet were shoulder width apart"). Statements that were irrelevant to technical performance, such as "the room was hot" or "I jumped up and down three times before each putt", were not included. Pearson's product-moment correlation coefficient indicated a high inter-rater reliability ($r = .91$, $n = 29$, $p < .001$). Orthogonal contrasts were used to test the prediction that the errorless group would accrue significantly fewer rules during the learning phase than would the other two groups combined, who would not differ from each other. No significant differences were found. All three groups accrued a similar number of rules during the learning phase: Mean (*SD*) number of rules reported = 4.27 (1.63), 3.11 (1.47), and 4.22 (1.94) for the errorless, errorful, and random groups, respectively.

Discussion

The golf putting performance of errorless and errorful learners was compared during a delayed retention test, secondary task transfer test, and novel distance transfer test. Errorless learners made fewer errors during the retention test than did errorful learners, as predicted. When a secondary task load was imposed the performance of the errorful learners deteriorated, whereas the performance of the errorless learners was unaffected, suggesting that the former had learned in S-mode and the latter in U-mode. All groups transferred equally well to the novel distance.

The errorless group performed their last learning trial from a distance of 200 cm, whereas the errorful group performed their last learning trial from the shortest distance (25 cm). It is possible that the higher performance of the errorless group during the 200-cm retention test is due to congruence between the performance distance during retention and performance distance on the preceding learning trial. If this explanation were correct we would expect the performance of the random group, whose last learning trial was performed at a distance of 175 cm, to be significantly higher than that of the errorful group but below or equivalent to that of the errorless group. This was not the case—the random group performed at the same level as the errorful group during retention suggesting that congruence does not account for the results reported.

Participants in the errorless condition were hypothesized to acquire the skill utilizing U-mode, which is associated with a lack of verbalizable knowledge. Verbal protocols failed to support this contention with all three groups reporting a similar number of technical rules post learning. Close inspection of the learning-phase data indicates that participants in the errorless condition began to make significantly more errors from the fourth block of trials onwards (100 cm to 200 cm). It is possible that the performance of this group became gradually more explicit as errors were made in the later trials. That is, performance during the first three blocks of practice was supported by unselective, implicit processes, which were replaced by selective, explicit hypothesis-testing processes as errors became more common in the latter half of the learning phase. This would suggest that initially learning under implicit conditions confers robustness to performance under dual-task conditions even if explicit rules are subsequently accumulated. A second experiment was carried out to establish whether errorless learners utilized U-mode during the first three blocks of learning.

EXPERIMENT 2

Two experimental conditions were utilized to test the proposal that errorless learners in the previous experiment utilized U-mode early in learning, whereas errorful learners utilized S-mode. The errorless condition required participants to perform the golf putting task from the first three distances utilized in Experiment 1 (25, 50, and 75 cm), whereas the errorful condition required performance from 175, 150, and 125 cm. To test the implicit nature of the performers' knowledge, verbal protocols were collected, and a secondary task transfer test, performed at a distance of 100 cm, was again employed. As the two conditions approach the transfer distance from different distances, their performance cannot be directly compared. A control group and an experimental group were therefore included in each condition to allow assessment of the effects of secondary task loading, independent of performance change due to transfer to the new putting distance. It was predicted that the errorless learners would report fewer explicit rules than the errorful learners and would demonstrate robustness under secondary task loading.

In addition to verbal protocols and secondary task loading, subjects were filmed in order to identify the number of visible changes that they made to their putting technique. Participants learning in S-mode are assumed to test hypotheses about how best to perform the skill. Visible modifications made by the performer to their putting technique may reflect this hypothesis-testing strategy. Participants who do not make errors should not need to change their technique substantially and should, therefore, make fewer visible changes to their putting action.

Method

Participants

A total of 58 undergraduate students volunteered to participate. Participants were required to have no previous golfing experience. Three subjects failed to meet this criterion and were dropped from the study. The remaining subjects were randomly assigned to one of two conditions, errorless or errorful, which were further divided to form four groups, errorless experimental (n = 14), errorless control (n = 13), errorful experimental (n = 14), and errorful control (n = 14). Of the participants, 8 were tested at a later date to the original sample in order to increase sample size and statistical power. All conditions remained identical, and no differences were found between this subset of participants and the original participants; therefore all reported statistical tests involve the entire sample. Ages ranged from 18 to 34 years (M = 21.02, SD = 2.81).

Apparatus

All apparatus was identical to that used in Experiment 1 with the addition of a Panasonic M40, VHS movie camera. The camera was tripod mounted and positioned in front and to the left of the participant at a distance that allowed all their movements to be recorded.

Procedure

The study was divided into two phases, learning and test. The learning phase consisted of three blocks of 50 trials performed from three distances. The errorless groups putted from distances of 25 cm, 50 cm, and 75 cm, respectively, whereas the errorful groups putted from distances of 175 cm, 150, cm and 125 cm, respectively. At the end of the Learning Phase, all participants completed verbal protocols describing any "rules, knowledge or methods" they had used or become aware of using during practice.

The test phase consisted of one block of 50 trials from a distance of 100 cm, forming a transfer test. During the transfer test, participants in the experimental groups were required to hole as many balls as possible while performing a secondary task. The task required participants to monitor and subsequently report the number of high-pitched tones in a random array of high- and low-pitched tones presented at a rate of one per 1500 ms. Participants in the control groups performed the putting task only. All participants were filmed throughout the learning phase.

Results

Learning phase

A Group × Block (4 × 3) ANOVA with repeated measures on the latter factor was computed. Significant main effects of block, $F(2, 102) = 3.53$, $p = .03$, and group, $F(3, 51) = 143.21$, $p < .001$, were found. A highly significant interaction was also evident, $F(6, 102) = 33.93$, $p < .001$. Post hoc analysis revealed that both errorless groups performed at a higher level than the errorful groups. The performance of the two errorless groups tended to decline over blocks, whereas the performance level of the errorful groups tended to increase, accounting for the effect of block and the interaction. As in Experiment 1, the results of this analysis bring no unexpected revelations. The errorless groups putted at shorter distances than the errorful, which accounts for their better performance and the group effect. The errorless groups putted from successively longer distances and the errorless from shorter distances. The effect of block and the interaction are consistent with this observation.

The errorless groups were predicted to commit fewer errors than the errorful groups due to the shorter putting distances used in the learning phase. The control and corresponding experimental groups in each condition were predicted to perform at similar levels. Orthogonal contrasts, with total number of errors committed during the learning phase as the dependent measure, indicated that the errorless groups made fewer errors than did the errorful groups, $t(51) = -20.87$, $p < .001$. The errorless experimental and errorless control groups did not differ from each other, nor did the errorful experimental and errorful control groups ($p > .05$). Mean (*SD*) total number of unsuccessful putts during the three learning blocks was 17.71 (12.07), 9.54 (6.75), 86.42 (19.07), and 94.14 (13.25) for the errorless experimental, errorless control, errorful experimental, and errorful control groups, respectively (Figure 3).

Transfer test

It is traditional to run either a Group × Block (4 × 2) ANOVA with repeated measures on the block factor or a one-way ANOVA on transfer performance to compare the effect of experimental manipulations on multiple groups. However, for the experiment reported here this analysis is inappropriate. The errorless and errorful groups approached the transfer test from different distances. The errorless groups transferred from 75 cm to 100 cm, whereas the

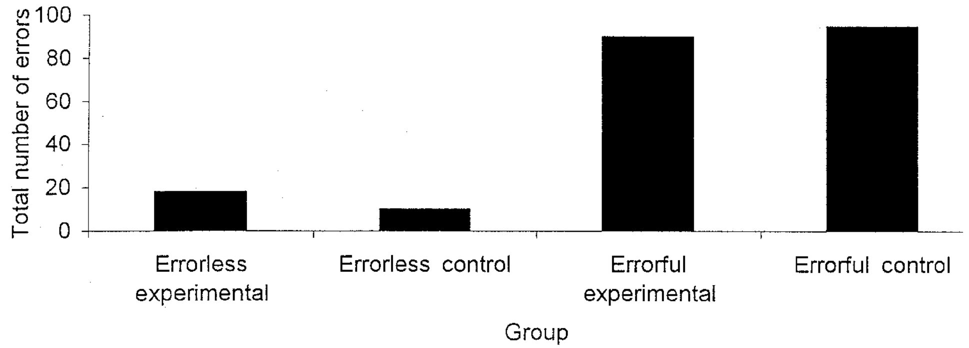

Figure 3. Mean total number of errors made by each group during the learning phase.

errorful groups transferred from 125 cm to 100 cm. Thus, the task became more difficult for the errorless groups and easier for the errorful groups, which may differentially affect performance on the transfer test trials. Additionally, it is unsuitable to conclude any affect of secondary task loading on performance without comparing it with unloaded performance. For example, if we found that the secondary task group performed at a higher level than an unloaded group we might conclude that secondary task loading is beneficial to performance. Clearly, this would be an unreasonable assumption if the secondary task group were actually performing at a lower level than they had previously without the load. Previous performance must be utilized to fully assess the effect of secondary task loading on performance, not simple comparisons between groups who may or may not be performing at different absolute performance levels. For these reasons, a direct comparison between all four groups is unsuitable. Therefore, two separate Group (experimental vs. control) x Block (Block 3 vs. transfer) ANOVAs with repeated measures on the block factor were carried out to determine the effect of secondary task loading on the two learning conditions.

A significant effect of block, $F(1, 25) = 11.93$, $p = .002$, was found for the errorless condition. Both groups made fewer successful putts during the transfer test. However, neither an effect of group, $F(1, 25) = 3.28$, $p = .08$, nor an interaction, $F(1, 21) = 0.323$, $p = .58$, was found for the errorless condition, suggesting that the errorless experimental group was unaffected by the imposition of a secondary task load (Figure 4).

A significant effect of block, $F(1, 26) = 46.39$, $p < .001$, and a Group × Block interaction, $F(1, 26) = 8.74$, $p = .007$, was found in the errorful condition. Inspection of Figure 4 illustrates that the performance of the errorful control transferred better to the easier distance of 100 cm than did that of the errorful experimental group. The errorful experimental group suffered a breakdown in performance under the secondary task load but the errorless experimental group did not.

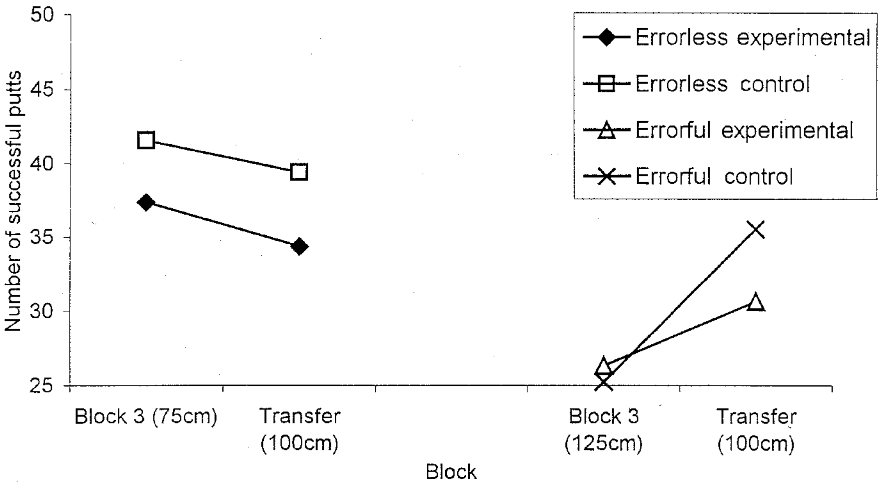

Figure 4. Mean number of successful putts made during the last block of the learning phase (Block 3) and during the transfer test (transfer).

To discount the possibility that the experimental groups from each condition allocated differing amounts of attentional resources to the primary and secondary task, a one-way ANOVA, with absolute percentage accuracy on the tone-counting task as the dependent measure, was carried out. No significant differences were found between the errorless experimental and errorful experimental groups, $F(1, 26) = 0.01$, $p = .94$. No correlation was found between tone counting accuracy and change in performance under secondary task loading ($r = .07$, $n = 27$, $p = .88$) so differing allocation of attentional resources to the primary and secondary tasks does not account for the effects of the secondary task load on primary task performance. Mean (*SD*) tone-counting accuracy was 95.16% (5.36) and 95.32% (4.94) for the errorless experimental and errorful experimental groups, respectively.

One might predict that the performance of the errorless groups should be higher than that of the errorful groups, based on the hypothesis adopted in Experiment 1 that errorless learning leads to better performance than errorful learning. Examination of Figure 4 indicates that this is generally true. Orthogonal contrasts indicated that the errorless control and experimental groups combined performed at a marginally higher level than did the errorful control and experimental groups combined, $t(51) = 1.98$, $p = .053$. No differences were evident between the control and experimental groups in either condition ($p > .05$).

Verbal protocols

Two independent raters assessed the number of rules reported by each subject. The criteria used in Experiment 1 were again employed. Pearson's product–moment correlation coefficient indicated a high inter-rater reliability ($r = .91$, $n = 55$, $p < .001$). Orthogonal contrasts were used to test the specific predictions that the errorless groups would accrue significantly fewer rules during the learning phase than the errorful groups, and the number of rules reported by the experimental and corresponding control group in each condition would not differ. No significant differences were found. It appears that, contrary to our predictions, all four groups accrued a similar number of rules during the learning phase (Figure 5).

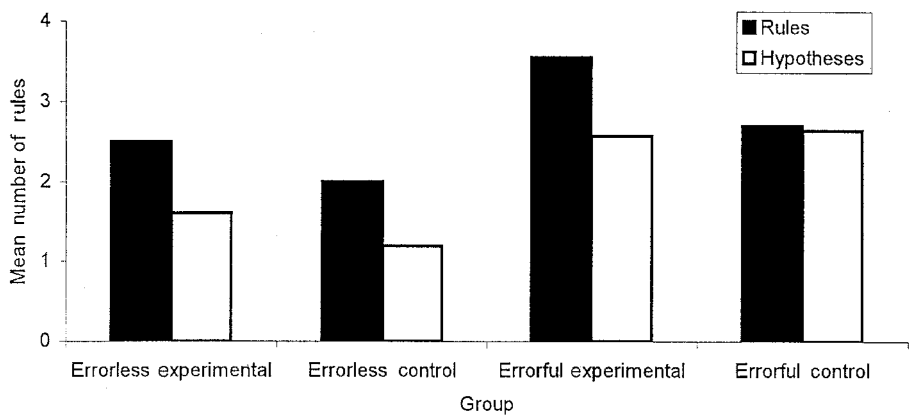

Figure 5. Mean number of rules and hypotheses reported by each group following the learning phase.

Our original conceptualization of S-mode learning stated that subjects test hypotheses about how best to perform the task. The analysis of the verbal protocols used here included any statements that indicated technical knowledge of the putting skill. For example, a participant might write "I held my left hand beneath my right and bent my arms". However, this statement gives no indication as to whether the subject actually thought about the positioning of their arms in relation to the task outcome. They may have simply remembered this "rule" retrospectively when prompted at the end of the learning phase but did not think about it during performance (Berry & Broadbent, 1984; Ericsson & Simon, 1984; Reber & Lewis, 1977). If this was the case, we would be unwise to conclude that this subject had learnt selectively.

Additional analysis of the verbal protocols, with slightly different criteria, was therefore carried out. Statements that indicated that the performer had tested hypotheses while putting were included; retrospective statements that may not have been used or thought about during performance of the putting task were excluded. For example, the statements "I adjusted the position of my feet to putt more balls" and "If the ball went to the right of the hole I hit the next one more to the left" indicate that the participant hypothesized a relationship between their actions and their outcomes while putting and that this was included in the analysis. Statements such as "My knees were bent" and "My feet were apart" that do not suggest hypothesis testing during performance and appear retrospective were not included. This second analysis better reflects the hypothesis-testing concept proposed.

Two independent raters counted the number of hypothesis-testing statements reported by all participants. Inter-rater reliability as measured by Pearson's correlation coefficient was high ($r = .94$, $n = 55$, $p < .001$). Both raters appear to be consistent in their use of the hypothesis-testing criteria proposed. Again, orthogonal contrasts were employed to test the specific predictions used in the first analysis. A significant difference between the number of hypotheses reported by the errorless groups and that reported by the errorful groups was found, $t(51) = -3.90$, $p < .001$. No differences were found between the experimental and corresponding control group in each condition. Participants in the errorless condition reported fewer hypotheses than those in the errorful condition: mean (*SD*) = 1.61 (1.23) and 1.19 (0.75) for the errorless experimental and control groups, respectively and mean (*SD*) = 2.57 (1.47) and 2.64 (0.99) for the errorful experimental and control groups, respectively. This suggests that the errorless groups learnt the putting skill via U-mode, whereas participants in the errorful condition utilized S-mode (Figure 5).

To add support to these findings the same "hypothesis-testing" analysis was carried out on the verbal protocols from Experiment 1. Inter-rater reliability was high ($r = .91$, $n = 27$, $p < .001$). A one-way ANOVA with number of hypothesis-testing statements as the dependent measure indicated a significant effect of group, $F(2, 28) = 5.33$, $p = .01$. Newman-Keuls a posteriori test indicated that the errorful group reported significantly more hypothesis testing statements than did the errorless and random groups, which did not differ from each other. Thus, partial support is provided for the contention that errorless performers may use an unselective mode of skill acquisition.

Video analysis

The number of visible adjustments that participants made to their technique was hypothesized to reflect the number of hypotheses being tested during learning. Adjustments to

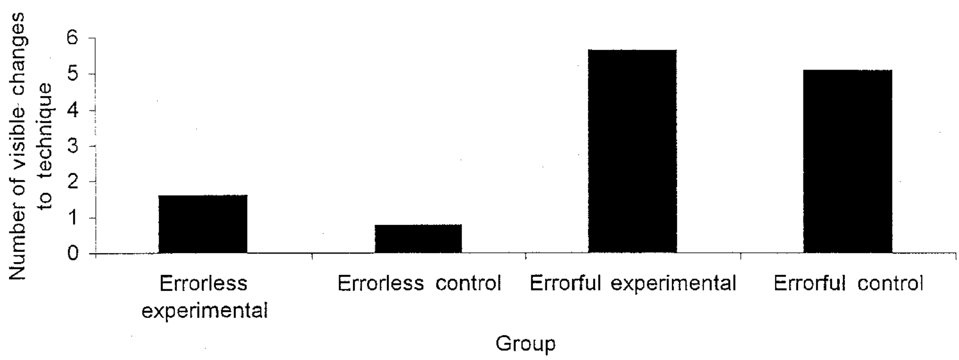

Figure 6. Mean number of visible adjustments to the putting technique made during the learning phase.

technique included such movements as changing foot position, grip, bending the elbows, and changing whole body position relative to the ball. Adjustments were counted if they were maintained for at least two consecutive trials. Movements such as resting between putts were not included if the participant returned to their previously adopted position. Participants in the errorless condition were predicted to make fewer adjustments to their technique than those in the errorful condition. Two independent raters, who were blind to the experimental conditions and were unaware of the purpose of the experiment, assessed the total number of technique changes made by each participant during the learning phase. During their analysis, the independent raters were able to see the distance that participants putted from, which may potentially have biased their ratings due to the systematic differences between the errorless and errorful training distances; however, both raters reported that this did not affect their decisions. Inter-rater reliability was high, as indicated by Pearson's product–moment correlation coefficient ($r = .96$, $n = 55$, $p < .001$).

Orthogonal contrasts, taking number of visible changes to the putting technique during the learning phase as the dependent measure, indicated that participants in the errorful groups made significantly more visible adjustments to their technique than did participants in the errorless groups, $t(51) = -5.41$, $p < .001$. The number of visible adjustments made by the experimental and corresponding control groups in each condition did not differ (Figure 6). Mean (*SD*) number of visible adjustments to technique during the learning phase were 1.57 (1.38), 0.73 (1.17), 5.64 (3.21), and 5.04 (4.34) for the errorless experimental, errorless control, errorful experimental, and errorful control, respectively. These findings were verified by traditional analyses (one-way ANOVA and Newman–Keuls a posteriori tests). The results support the second analysis of the verbal protocols suggesting that the hypothesis-testing criterion may be a more reliable strategy for analysing the verbal protocols than the all-inclusive "rules" criterion.

Discussion

Participants were exposed to either errorless or errorful learning environments. They were subsequently asked to perform a secondary task transfer test and to report their verbalizable knowledge pertaining to the task. Errorless learning conditions ameliorated the effects of the secondary task load on primary task performance during the transfer test. Participants who experienced errorful learning conditions experienced performance breakdown under secondary task loading relative to participants who performed without a secondary load. The results support the contention that errorless learning is mediated by an unselective learning mode, which is robust to the effects of secondary tasks and does not require abstract working memory, whereas errors during learning initiate a selective learning mode, which does require abstract working memory.

Participants' verbal protocols, scored for the number of technical rules reported, again failed to support the secondary task findings. All groups reported a similar number of technical rules. However, a second analysis of the verbal protocols that used a stricter hypothesis-testing criterion did support the proposal that errorless participants learnt via U-mode, whereas errorful participants learnt the putting task via S-mode. Video analysis of the number of modifications made to the participants' putting technique supported the findings from the second analysis of the verbal protocols. Errorful participants appeared to make more changes to their technique than did errorless participants, supporting the idea that only they were testing hypotheses.

GENERAL DISCUSSION

The studies reported here examined the possibility that when errors are prevented or considerably reduced during learning, an unselective mode of acquisition is adopted, but when errors are present and must be corrected a selective mode of acquisition is adopted. Errorful learners were predicted to form hypotheses about how to correct their errors during acquisition of a complex motor skill, golf putting. This strategy is characteristic of a selective learning mode and should result in the accumulation of a pool of explicit, verbalizable rules and breakdown of performance under secondary task loading. Errorless learners were predicted to passively learn the golf putting skill without the need to test hypotheses because no errors were made. They were expected to accumulate little verbal knowledge and demonstrate robust performance under dual-task conditions, characteristic of U-mode learning.

Both experiments supported the contention that the reduction of errors during learning would promote the adoption of an unselective mode of learning but the presence of errors would instigate a selective mode of acquisition. Errorful learners in both experiments suffered a breakdown in performance under dual-task conditions suggesting that some aspects of their performance were reliant on abstract working memory. The performance of the errorless learners, however, was not affected by the imposition of a secondary task. Analysis of the participants' verbal protocols using a hypothesis-testing criterion also supported the contention that errorless learning initiates an unselective learning mode. In both studies, errorless learners reported fewer hypothesis-testing strategies than did the errorful learners.

Relatively errorless acquisition of the golf putting skill produced a higher subsequent level of performance during retention than did errorful acquisition, contrary to previous findings. Previous studies have reported that errorless learners generally demonstrate poorer performance during non-guided retention trials. In a recent study Wulf et al. (1998) had participants learn to perform a ski-simulation task with or without physical guidance (with or without ski poles, respectively). They reported similar benefits of guided learning (where errors are reduced) for movement amplitude during learning but not during retention performed under non-guided conditions. However, guided learners adopted a more efficient movement pattern than did non-guided learners, suggesting that physically guided practice was superior to non-guided practice for skill acquisition. Wulf et al. proposed that guided practice allowed the performer to experience the target movement pattern at an earlier stage in learning than would normally be the case during non-guided practice. If the errorless learners in the current experiment acquired the correct movement pattern earlier in learning than the errorful learners, it is not surprising that they might perform at a higher level during the retention test.

An alternative explanation for the higher performance level of errorless learners in Experiment 1 may be the similarity of conditions during learning and retention. Previously, guided learning has been followed by non-guided retention; this transfer to novel conditions probably accounts for the poorer performance of guided learners in these studies. The similarity between conditions in the learning phase and retention phase in Experiment 1 may account for the continued higher performance of the errorless group relative to the other groups, consistent with previous literature that reports that when learning conditions are closely matched with retention conditions performance will be optimal (Macrae & Holding, 1965a). Novel transfer performance was equivalent for all three groups, with the errorless group continuing to perform at a higher level than the other groups. Previous research has demonstrated poor transfer for both errorless learning (see Singer, 1977) and implicit learning (Berry & Dienes, 1993). The surface used in this experiment was flat and even. When putting at the new distance subjects needed only to adjust the power of their shot. A transfer test to a sloped surface may provide different results because errorless learners now have to change aspects of their technique, of which they may not be immediately aware. Errorful learners may be accustomed to changing their technique and, therefore, may transfer better under these conditions (Wulf & Schmidt, 1994).

A number of researchers have proposed different terms to describe essentially the two modes of learning proposed by Berry and Broadbent (1988). For example, Roberts and MacLeod (1995) describe two modes of learning that are similar in concept to Broadbent and colleagues' selective and unselective modes. The first, strategic learning, involves a hypothesis-testing strategy similar to selective mode. The knowledge gained is explicable and susceptible to disruption from secondary cognitive tasks. The second form of learning, which proceeds in an incidental fashion, is non-strategic learning and is similar to unselective mode. Roberts and MacLeod implied that any manipulation that prevents the use of strategic processing would increase the use of non-strategic processes. For example, reducing the necessity to test hypotheses by reducing the number of errors experienced during acquisition may effectively implement a non-strategic mode of learning. However, it is probable that strategic and non-strategic learning both contribute to skill acquisition but in differing proportions depending on the learning conditions.

Gentile (1998) proposed two processes that mediate functional skill acquisition. These processes are also similar in concept to Berry and Broadbent's (1988) selective and unselective modes, although Gentile does not explicitly refer to them as such. The first process describes the functional relationship between the performer and their environment and is explicit (S-mode). The second, implicit, process determines the functional dynamics of the movement (U-mode)—that is, the efficient patterning of muscle activation to bring about skilled movement with minimum effort, characteristic of Fitts and Posner's (1967) autonomous stage of performance. Gentile suggested that these processes act in parallel and that the explicit process is rapid, whereas the implicit process is slow and requires substantial practice. When performing a golf putting task both explicit and implicit processes might be used in parallel. The performer normally uses information from the environment and the outcome of their actions to explicitly establish the relationship between their actions and the desired outcome. That is, they explicitly modify their technique, by testing hypotheses, to conform to the task demands.

The manipulation used during the learning phase in these experiments may have affected the relative contributions of the explicit and implicit processes, described by Gentile (1998), to performance. Errorless learning reduced the contribution of explicit processes because the functional relationship between the performer and the environment was highly constrained. This may have promoted the formation of the implicit knowledge base governing the underlying functional dynamics of the skill. The performance of errorful learners was dependent upon the correct identification of the functional relationship between the performer and the environment. This relationship may have been difficult to establish when errors were frequent. Attentional resources may have been selectively allocated to the identification of the functional relationship, thereby interfering with acquisition of the functional dynamics. This would suggest that the performance of the errorful learners was mediated by a larger contribution from explicit than from implicit processes, with the opposite being true for the errorless learners. The adoption of an explicit/implicit processing mode during learning explains why the prevention of explicit processing, by imposing an additional cognitive load, affected the performance of errorful learners but not that of errorless learners.

This proposal is similar in spirit to the claims of Curran and Keele (1993), who utilized a serial reaction time task to produce evidence of attentional and non-attentional learning mechanisms. The attentional mechanism encodes the relationship between successive events and requires attention, whereas the non-attentional mechanism operates with minimal attentional requirements. They proposed differential effects of distraction on these mechanisms, with the attentional mechanism being disabled by secondary task loads but the non-attentional mechanism remaining unmodified. Both mechanisms operate in parallel and independently in normal situations. It is possible that the non-attentional mechanism made a larger contribution to the performance of errorless learners than to that of errorful learners, who required a large contribution from the attentional mechanism for efficient performance. This differential contribution of attentional and non-attentional mechanisms may account for the performance differences under secondary task loading found here.

An explanation that does not demand recourse to a parallel-processing, multiple-mode theory of skill acquisition comes from a suggestion by Ackerman (1988). Ackerman proposed that increasing the variability of practice increases cognitive input and prevents transition to the autonomous stage of performance, whereas reducing variability or promoting the consistency of practice (Wickens, 1989) promotes automisation. The errorless conditions utilized here may have promoted the transition into automatic processing, which has been associated with lower attentional demand (Schneider, Dumais, & Shiffrin, 1985). This may account for the robustness displayed by the errorless groups under secondary task loading. The number of trials used here does not seem sufficient to bring about this level of automatization; however, this explanation cannot be discounted. Future studies are needed to address these possibilities and better define the conceptualization of implicit and explicit motor learning.

In conclusion, it appears that skills acquired with frequent errors during learning place a greater demand on explicit, attention-demanding resources than do skills acquired in an error-free learning environment. The reduced demand on attention confers robust performance under distraction to the performer. Previous studies have demonstrated that implicitly learnt skills are afforded protection from the debilitating effects of psychological stress (Hardy et al., 1996; Masters, 1992). Robustness of performance under stress is a desirable quality for all participants in sport. The errorless learning procedure seems to confer an implicit quality to the learner's performance. Future studies might address the robustness of errorlessly learnt motor skills under psychological pressure to confirm the implicit nature of this procedure.

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