The Quarterly Journal of Experimental Psychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pqje20

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To cite this article: Guillaume Chauvel, François Maquestiaux, Alan A. Hartley, Sven Joubert, André Didierjean & Rich S. W. Masters (2011): Age effects shrink when motor learning is predominantly supported by nondeclarative, automatic memory processes: Evidence from golf putting, The Quarterly Journal of Experimental Psychology, DOI:10.1080/17470218.2011.588714

To link to this article: http://dx.doi.org/10.1080/17470218.2011.588714

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
iFirst, 1–14

Psychology Press
Taylor & Francis Group

Age effects shrink when motor learning is predominantly supported by nondeclarative, automatic memory processes: Evidence from golf putting

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Can motor learning be equivalent in younger and older adults? To address this question, 48 younger ($M = 23.5$ years) and 48 older ($M = 65.0$ years) participants learned to perform a golf-putting task in two different motor learning situations: one that resulted in infrequent errors or one that resulted in frequent errors. The results demonstrated that infrequent-error learning predominantly relied on nondeclarative, automatic memory processes whereas frequent-error learning predominantly relied on declarative, effortful memory processes: After learning, infrequent-error learners verbalized fewer strategies than frequent-error learners; at transfer, a concurrent, attention-demanding secondary task (tone counting) left motor performance of infrequent-error learners unaffected but impaired that of frequent-error learners. The results showed age-equivalent motor performance in infrequent-error learning but age deficits in frequent-error learning. Motor performance of frequent-error learners required more attention with age, as evidenced by an age deficit on the attention-demanding secondary task. The disappearance of age effects when nondeclarative, automatic memory processes predominated suggests that these processes are preserved with age and are available even early in motor learning.

Keywords: Cognitive ageing; Motor learning; Frequency of errors; Memory; Attention.

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Jon Maxwell passed away on Sunday 25th January 2009. We were privileged to have the opportunity to work with Jonny Max. This research was supported by a doctoral fellowship from the Ministère de l'Enseignement Supérieur et de la Recherche to Guillaume Chauvel. Sven Joubert is supported by a Chercheur Boursier award from the Fonds de la Recherché en Santé du Québec (FRSQ). Rich S. W. Masters is supported by the Research Grants Council of the Hong Kong Special Administrative region (HKU 748709H). We thank Eric Ruthruff for his commentary and invaluable insights on an earlier draft of the manuscript.

http://www.psypress.com/qjep
DOI:10.1080/17470218.2011.588714

Older adults, relative to younger adults, not only often need much longer to learn a new motor skill, but also fail to develop the same level of expertise (e.g., for evidence with manual motor skills, see Harrington & Haaland, 1992; Howard & Howard, 1997; McNay & Willingham, 1998; Pratt, Chasteen, & Abrams, 1994; Seidler, 2006, 2007). For instance, Pratt et al. (1994) observed that the ballistic and corrective submovements involved in a rapid aiming movement toward a target changed across extended practice in younger but not older adults. Nevertheless, it is well documented that declarative, effortful memory processes are degraded with advancing age, while nondeclarative, procedural, automatic memory processes show few or no age deficits (for a review, see Hoyer & Verhaeghen, 2006). In what follows we argue that there are theoretically sound reasons to hypothesize that intact procedural memory processes should provide a substrate that would allow equivalent learning of new motor skills in younger and older adults under the right learning conditions.

Sequential model of skill acquisition

The classical model of perceptual–motor skill acquisition, initially proposed by Fitts (1964; see also Fitts & Posner, 1967) and extended to intellectual skills by Anderson (1982), is a stage model that proceeds sequentially from cognitive/declarative to autonomous/procedural stages of learning (for a review of empirical evidence consistent with this model in the perceptual–motor and intellectual skill domains, see Rosenbaum, Carlson, & Gilmore, 2001). This model suggests that declarative memory processes are mainly involved early in learning, while nondeclarative memory processes become more important later in learning. Fitts (1964) hypothesized that the declarative stage of learning allows the acquisition of the basic rules of a task and, if necessary, their articulation. This implies that early learning culminates in knowledge representations that are generally accessible to conscious report (i.e., declarative knowledge). In contrast, the nondeclarative stage of learning allows the automatization of task procedures so that they can be completed more rapidly and are less vulnerable to interference. This implies that late learning culminates in knowledge representations that generally are not open to conscious report (i.e., procedural knowledge).

How can we know whether performance mainly depends on declarative or procedural processing? In line with the views of Schneider, Dumais, and Shiffrin (1985), we hypothesize that declarative memory processes rely upon a controlled mode of information processing, whereas nondeclarative memory processes rely upon a more automatic mode of information processing. Specifically, effort and attentional resources are required during the early, declarative stage of learning but to a much lesser extent during the late, nondeclarative stage of learning. Consequently, the essential characteristic of the declarative stage of learning is that skill performance should be impaired by the imposition of a concurrent, attention-demanding secondary task. In contrast, the essential characteristic of the nondeclarative stage of learning is that skill performance should be relatively unaffected by the imposition of a cognitive secondary task.

Can nondeclarative, automatic memory processes predominate early in motor learning?

Masters (1992; for a review, see Masters & Maxwell, 2004) found that, early in motor learning, declarative, effortful memory processes do not necessarily predominate over nondeclarative, automatic memory processes. Masters asked participants to perform a new motor skill (golf putting) while simultaneously performing an attention-demanding cognitive task (random letter generation). He speculated that this dual-task learning situation would encourage proceduralized, automatic control because the additional cognitive task would reduce the possibility for effortful, declarative learning. Consistent with this speculation, Masters found that motor-skill performance of dual-task learners was at transfer unaffected by the pressure induced by a financial reward based on evaluations by an expert golf player. In contrast, the same stressful intervention resulted in disrupted motor-skill performance in participants who learned the golf-putting task with no secondary task. The dual-task learners also reported fewer verbal rules of execution than the single-task learners. Taken together, these results suggest that the influences of declarative, effortful and nondeclarative, automatic memory processes guiding motor control and learning were quantitatively different between the two learning groups: mainly declarative and effortful for single-task learners and mainly nondeclarative and automatic for dual-task learners (for converging evidence that dual-tasking during learning allows the development and the use of declarative knowledge, see Beilock & Carr, 2001). Therefore, the findings of Masters (1992) are consistent with the view that automatic, procedural knowledge can develop and support performance early in motor-skill learning, even at a stage that is usually thought to be primarily characterized by effortful, declarative memory consolidation.

Masters (1992) found that the number of successful putts steadily increased across learning sessions, but to a lesser extent for dual-task than single-task learners. To explain this quantitative difference and following a suggestion by Baddeley and Wilson (1994) about the functional specificity of explicit and implicit memory processes, Maxwell, Masters, Kerr, and Weedon (2001) proposed that declarative, effortful memory processes allow one to respond to errors by recollecting experience from past events and then selectively eliminating errors in subsequent trials. In contrast, nondeclarative, automatic memory processes simply encode the occurrence of events in an unselective fashion and do not provide a basis for effortful attempts to prevent future errors (for a similar view but in terms of selective and unselective modes of learning, see Berry & Broadbent, 1988). Consequently, Maxwell et al. speculated that the dual-task learners in the Masters (1992) study were less able than single-task learners to avoid repetition of errors while performing the golf-putting task. In other words, the authors speculated that their dual-task learners' knowledge representations were constructed from both successful and unsuccessful actions, thus explaining their poorer level of performance than that of the single-task learners who had developed more conscious, declarative strategies to avoid errors.

Nondeclarative, automatic memory processes predominate during infrequent-error learning

Maxwell et al. (2001, Experiment 2) assumed that errors are added to the declarative knowledge base and encourage continued use of declarative, effortful memory processes. Consequently, they speculated that learning environments that are sufficiently easy to cause infrequent errors (e.g., see Prather, 1971) should promote the development and the predominance of an efficient base of automatic, procedural knowledge. Indeed, the overall number of unsuccessful actions that comprise the knowledge base elaborated throughout such learning should be minimized (for the efficacy of this learning method, also called "errorless learning" in cognitive interventions for amnesic patients, see Kessels & De Haan, 2003). To test this speculation, Maxwell et al. examined the effects of two learning methods on the type of knowledge underlying performance of a golf-putting task: (a) an infrequent-error learning method in which participants performed a block of 50 trials of a golf-putting task from a distance near the hole (25 cm) and in subsequent blocks increased in steps of 25 cm up to 75 cm and (b) a frequent-error learning method in which participants performed the same motor task but started at a distance further from the hole (175 cm), which was then decreased by steps of 25 cm up to 125 cm. The methods provided two opposite manipulations of the overall frequency of errors made during learning, much lower for infrequent-error learners (9.1%) than for frequent-error learners (60.2%). In a transfer test, half of the infrequent-error and frequent-error learners performed only the golf-putting task (single-task transfer group) at a new, intermediate distance of 100 cm, whereas the other half performed the golf-putting task in conjunction with an attention-demanding secondary tone-counting task (dual-task transfer group). Maxwell et al. (2001, Experiment 2) observed that, at the transfer distance of 100 cm, the overall level of performance (single-task and dual-task transfer groups combined) was slightly higher for infrequent-error learners than for frequent-error learners. They also found that the secondary cognitive task did not influence the motor performance of infrequent-error learners, but did impair the performance of frequent-error learners. In addition, the amount of self-reported declarative knowledge presumably used during the motor-skill execution (i.e., the number of strategies reported) was smaller for infrequent-error learners than for frequent-error learners, implying that there were quantitative differences in the different types of knowledge used by the two learning groups. This converging evidence suggests that, even relatively early in motor learning, nondeclarative, automatic memory processes can supersede declarative, effortful memory processes if errors occur infrequently.

GOALS AND PREDICTIONS OF THE CURRENT STUDY

The implications of these findings for motor-skill acquisition in older adults are clear and direct. We know, from the cognitive ageing literature, that age differences in nondeclarative, procedural memory are small. We also know, from the work of Masters and Maxwell (Masters, 1992; Masters & Maxwell, 2004; Maxwell et al., 2001), that, in younger adults, procedural memory processes can predominate over declarative, effortful memory processes even in the very early stages of learning. If this is true for older adults, then training procedures that encourage development primarily of procedural memories should result in learning that either is equivalent in older and younger adults or, at least, shows very small age differences.

This prediction was addressed in the present study by taking advantage of the procedure developed by Maxwell et al. (2001, Experiment 2). The procedure revealed differences in the types of memory processes used by younger adults when they learned the motor skill of golf putting in an infrequent-error condition (i.e., predominance of nondeclarative, automatic memory processes) compared to when they learned it in a frequent-error learning condition (predominance of declarative, attention-demanding memory processes). The critical indicator of this distinction was that motor performance, when performed in conjunction with a secondary attention-demanding task, was unimpaired for infrequent-error learners but impaired for frequent-error learners.

Our basic approach consisted of two steps. The first step, the learning phase, consisted of randomly assigning 48 younger and 48 older adults either to a method that should allow infrequent-error learning or to a method that should allow frequent-error learning. Infrequent-error learners performed four blocks of 40 trials, starting near the hole (25 cm) in the first block, then moving 25 cm further away in each subsequent block, ending at 100 cm. Frequent-error learners performed four blocks of 40 trials, starting far from the hole (225 cm), then moving 25 cm closer each block, ending at 150 cm. The second step of our approach, the transfer phase, consisted of comparing motor-skill performance at a new distance of 125 cm (exactly in-between the distances used by the two learning groups) when performed concurrently with a tone-counting task[1] (for one half of the participants) or in a single-task condition (for the other half of the participants).

Our predictions stem from three assumptions: (a) nondeclarative, procedural, automatic memory processes are active even early in learning; (b) infrequent-error learning favours the use of nondeclarative, procedural, automatic memory processes over declarative, effortful memory processes, whereas frequent-error learning favours the use of declarative, effortful memory processes over nondeclarative, procedural, automatic memory processes; and

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[1] Relative to Maxwell et al. (2001), the present tone-counting task was more difficult in terms of perceptual discrimination (a single tone embedded in a stream of single tones and pairs of tones, instead of a high-pitched tone embedded in a stream of high-pitched and low-pitched tones) and of presentation rate (1.2 s per stream instead of 1.5 s). The rationale for using a more difficult tone-counting task was to preclude participants from directing attentional resources toward motor execution between two successive tones—in other words, to reduce the likelihood of task-switching strategies in the transfer test.

(c) nondeclarative, procedural, automatic memory processes encounter few or no age deficits, whereas declarative, effortful memory processes are altered with advancing age. Our first prediction is that, during the learning phase, the levels of motor-skill performance should be equivalent between younger and older participants in the infrequent-error condition, but should be poorer for older than younger participants in the frequent-error condition. Our second prediction is that, during the transfer phase, no dual-task interference should be observed for either younger or older infrequent-error learners, but that dual-task interference should be found for frequent-error learners and should be greater in older than younger participants.

Method

Healthy younger and older adults participated in a 1.5-hour experimental session. None of them reported previous golfing experience. Questionnaires and assessments of balance and general neuropsychological functioning were first administered, and then participants performed 160 golf-putting trials spread over four different distances from the hole (henceforth, this will be called the *learning phase*). Written recollections of memories related to the previous golf-putting trials were completed, and participants then performed the golf-putting task at a novel distance either in isolation or with a concurrent cognitive task (called the *transfer phase*). The five blocks were separated by breaks ranging from 4 to 5 min.

Participants

Forty-eight younger adults ($M = 23.5$ years, $SD =$ 3.3 years, range = 18–31 years, 24 women) and 48 older adults ($M = 65.0$ years, $SD = 3.7$ years, range = 59–71 years, 23 women) were recruited as volunteers from the Université Paris-Sud 11 (Orsay, France) and the surrounding local community. All participants gave their written informed consent before participation. The level of education was similar between the younger adults ($M = 15.6$ years, $SD = 2.1$ years) and older adults ($M = 15.3$ years, $SD = 3.1$ years), $t(94) < 1$. On a 10-point health-rating scale (10 = *excellent health*), the mean self-rating was slightly higher in younger adults ($M = 8.6$, $SD = 0.9$) than in older adults ($M = 8.1$, $SD = 1.1$), $t(94) = 2.72$, $p < .01$. Participants were screened for normal or corrected-to-normal vision and hearing using self-report. They also had no history of neurological disease and did not take any medication that may have affected cognition. The assessment of dynamic balance, using the Timed "Up and Go" Test (Podsiadlo & Richardson, 1991), indicated no abnormality for any of the younger and older adults (specifically, the slowest older adults did not exceed 10 s to complete the test). The Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) indicated no impaired global mental status among the 48 older adults (the lowest score of 27 was observed for 2 older adults). Psychometric tests were also conducted to better characterize the participants on different cognitive functions: attention and executive functions (Stroop Victoria from Regard, 1981; Trail Making A and B from Reitan & Wolfson, 1985) and short-term and working memory (Letter–Number Sequence from Wechsler, 1997). Descriptive statistics for general characteristics and scores for each test from both age groups are shown in Table 1, along with p values of independent-samples t tests comparing the means of younger and older adults on each general characteristic (except age) and test. As expected, cognitive performance was poorer in older adults than in younger adults on each explicit test that measured attention and executive functions (for reviews, see Allen, Ruthruff, & Lien, 2007; Hartley, 1992; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003) as well as on explicit tests that measured short-term and working memory (for a review, see Hoyer & Verhaeghen, 2006).

Apparatus

Participants attempted putts to a hole 11.5 cm diameter from varying distances, on an even, level artificial-turf indoor green (200 cm by 270 cm) raised 15 cm above ground level to allow a collecting duct to be fit beneath the hole. Top-Flite standard white golf balls were used. Identical right- and

Table 1. *Descriptive statistics for general information and tests measuring balance and cognitive function in younger and older participants*

	Younger adults (n = 48)			*Older adults (n = 48)*		
	M	*SD*	*Range*	*M*	*SD*	*Range*
General characteristics						
Mean age (years)	23.5	3.3	18–31	65.0	3.7	59–71
Years of education	15.6	2.1	12–20	15.3 *ns*	3.1	9–20
10-point health rating scale	8.6	0.9	7–10	8.1*	1.1	5–10
Tests						
Dynamic balance						
Timed Up and Go Test (time in s)	5.0	0.6	3.4–6.7	6.5*	1.2	4.6–10
MMSE (/30)				29.2	.9	27–30
Attention and executive functions						
Stroop Victoria (time on first plate)	10.2	1.4	7.7–15.1	12.3*	3.1	7.5–25.4
Stroop Victoria (time on second plate)	12.4	2.0	8.8–18.0	16.4*	4.4	9.4–30.0
Stroop Victoria (time on third plate)	17.3	3.4	12.2–25.5	26.7*	6.4	16.8–46.9
Trail Making A (time in s)	23.5	6.8	12.4–41.1	37.8*	10.9	19.5–82.0
Trail Making B (time in s)	45.5	11.5	23.7–68.1	80.0*	24.8	46.9–144.8
Short-term memory						
Letter–Number Sequence (scaled scores)	14.8	2.2	10–19	12.6*	2.9	7–18
Working memory						
Letter–Number Sequence (scaled scores)	12.9	2.2	9–19	10.1*	2.4	3–15

Note: MMSE = Mini-Mental State Examination.

*Indicates that the *p* value of independent-samples *t* tests comparing the means of younger and older adults fell below .001; *ns* = nonsignificant.

left-handed Odon putters (length 87 cm or 90 cm) were available to suit each participant's preference. The secondary tone-counting task condition, presented via wireless earphones, was performed by a PC-compatible computer equipped with E-Prime software (Version 2.0).

Procedure

The experiment was divided into two phases: the learning phase and the transfer phase. During the learning phase, participants performed four blocks of 40 trials from four distances. The frequent-error learners putted from distances of 225, 200, 175, and 150 cm, respectively, whereas the infrequent-error learners putted from distances of 25, 50, 75, and 100 cm, respectively. Participants were instructed to put as many balls as possible in the hole. They were informed that there was no time constraint to perform each block. All participants were then asked to "recall and write down a description of any details and thoughts related to golf putting that you have used in order to improve your putting performance during the learning phase. Specifically, think back and write down any rules and strategies you remembered having employed or became aware of using during the learning phase". Participants needed between 4 and 5 minutes to write down the description.

During the transfer phase, participants performed one block of 40 trials at a novel distance of 125 cm. Half of the infrequent-error and frequent-error learners were assigned to a control condition in which they performed only the putting (the *control transfer group*). The other half of the frequent-error and infrequent-error learners were assigned to an experimental condition in which they performed an attention-demanding tone-counting secondary task while simultaneously putting (the *experimental transfer group*). They were instructed to be as accurate as possible on the secondary task. The stimuli for the tone-counting task were single 15-ms tones (2,000 Hz) and pairs of 15-ms identical tones (2,000 Hz each) presented for 85 ms (intertone interval = 50 ms). There were equal numbers of single tones and tone pairs. Experimental transfer participants were required to monitor and count the number of single tones embedded in a random stream of single tones and pairs of tones presented at a rate of one stimulus per 1.2 s. Participants were familiarized with the tone-counting task by performing one sample of it in isolation (i.e., a sample of 30 tones, which lasted for 40 s approximately) before starting the learning phase. None of the participants reported any difficulties in discriminating the auditory stimuli used in the tone-counting task.

Overview of analyses

To assess the golf-putting performance during the learning phase, an analysis of variance (ANOVA) was conducted on the mean number of successful putts, with age group (younger or older) and type of transfer group (control or experimental) as between-subjects variables and block (1st, 2nd, 3rd, and 4th block) as a within-subjects variable. This ANOVA was carried out separately for each training condition, due to the absence of overlap between the putting distances of the two learning conditions. A Poisson regression analysis was conducted on the number of strategies reported to have been used during learning by the participants (because this dependent variable is count data), with age group, type of learning, and type of transfer group as between-subjects variables. To assess golf-putting performance during the transfer phase, we carried out an ANOVA, separately for each training condition, on the mean number of successful putts, with age group (younger or older) and type of transfer group (control or experimental) as between-subjects variables and block (4th block and block at the new distance of 125 cm) as a within-subjects variable. For each of the two learning subgroups assigned to the experimental condition (i.e., the dual task) during transfer, independent-samples t tests were carried out on the percentage accuracy on the tone-counting task with age group as a between-subjects variable. The normality of the distributions was assessed and confirmed for each dependent variable (number of successful putts, number of strategies reported, and percentage accuracy on the tone-counting task), using both visual inspection of the distributions and quantile–quantile analyses.

Results

Learning phase

Putting performance. Figure 1 shows the mean number of successful putts performed by younger and older adults across the four learning blocks in the infrequent-error and frequent-error learning conditions. In the infrequent-error learning condition, the overall number of successful putts was equivalent between younger adults ($M = 35.0$, $SD = 2.5$) and older adults ($M = 34.7$, $SD = 2.2$), $F(1, 44) < 1$ ($\eta_p^2 = .003$). The number of successful putts gradually decreased from short distances (e.g., at 25 cm: $M = 39.3$, $SD = 1.2$) to longer distances (e.g., at 100 cm: $M = 29.6$, $SD = 4.6$), $F(3, 132) = 117.37$, $p < .001$ ($\eta_p^2 = .727$). The type of transfer group did not influence the number of successful putts, $F(1, 44) = 1.98$, $p = .167$ ($\eta_p^2 = .043$). None of the two-way or three-way interactions between variables was significant (Fs < 1). In the frequent-error learning condition, the number of successful putts was overall significantly lower in older adults ($M = 15.3$, $SD = 4.7$) than in younger adults ($M = 20.6$, $SD = 3.3$), $F(1, 44) = 20.49$, $p < .001$ ($\eta_p^2 = .318$). The number of successful putts gradually increased from long distances (e.g., at 225 cm, $M = 13.6$, $SD = 5.5$) to shorter distances (e.g., at 150 cm, $M = 22.8$, $SD = 6.1$), $F(3, 132) = 47.93$, $p < .001$ ($\eta_p^2 = .521$). The number of successful putts was marginally higher in the experimental transfer group ($M = 19.0$, $SD = 4.4$) than in the control transfer group ($M = 16.9$, $SD = 5.0$), $F(1, 44) = 3.50$, $p = .09$ ($\eta_p^2 = .074$). No two-way or three-way interaction between variables was significant, Fs < 1. In sum, age-equivalent motor performance during learning was found when the learning environment was made easier by promoting success (i.e., infrequent-error learning) whereas a deficit of motor performance with age was found when the learning environment was made difficult

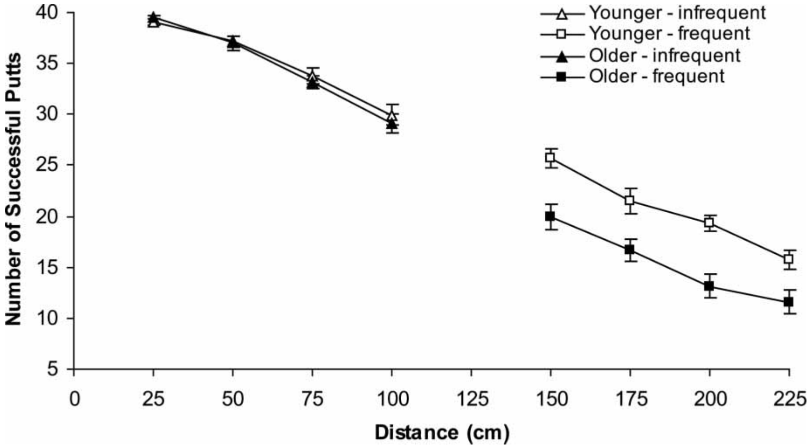

Figure 1. *Mean number of successful putts by younger and older participants as a function of distance from the hole in the learning phase for infrequent-error and frequent-error learning conditions. Bars show standard errors.*

by promoting failures (i.e., frequent-error learning).[2]

Reports of hypothesis testing. Each individual's written report following the learning phase was analysed by two independent raters. The raters tallied the number of statements that they considered to be consistent with the testing of strategies during execution of the golf-putting task—that is, statements that indicated that participants hypothesized a relationship between their actions and their outcomes. For instance, statements such as "If the ball fell too short of the hole I hit the next one harder" or "I adjusted the position of the head of the putter in order to hit the ball with a right angle" were counted. In contrast, statements that did not suggest hypothesis testing during motor execution, but only reflected episodic recollection of the golf-putting performance (such as "My knees were bent"), were not counted. The interrater reliability was high, $r(94) = .84$, $p < .01$. On average, 39.4% ($SD = 28.8\%$) of statements in the written reports were consistent with hypothesis-testing strategy, and 60.6% ($SD = 28.8\%$) were consistent with episodic recollection of the golf-putting performance. No differences in total percentage of statements were found between the groups. Consistent with the hypothesis-testing strategy prediction, the number of hypothesis-testing statements was greater in the frequent-error learners ($M = 1.63$, $SD = 1.0$) than in the infrequent-error learners ($M = 1.15$, $SD = 0.9$), Wald $\chi^2 = 4.15$, $p = .042$. Neither the main effect of age group nor the main effect of type of transfer group on the number of hypothesis-testing statements was significant, Wald χ^2s < 1. Also, none of the two-way interactions was significant, Wald χ^2s < 1. Finally, there was no

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[2] These findings cannot be accounted for by age differences in the duration necessary to perform a block of putts, as revealed by an ANOVA carried out with age group, type of transfer group, and type of learning as between-subjects variables and block as a within-subjects variable. First, the mean time necessary to perform a block of putts was equivalent between younger adults ($M = 4$ min 47 s) and older adults ($M = 4$ min 46 s), $F(1, 88) < 1$ ($\eta_p^2 = .001$). Second, there was a main effect of type of learning with the duration being shorter for infrequent-error learners ($M = 4$ min) than for frequent-error learners ($M = 5$ min 33 s), $F(1, 88) = 82.48$, $p < .001$ ($\eta_p^2 = .484$). Third, the type of learning effect combined additively with age group, $F(1, 88) = 1.33$, $p = .253$ ($\eta_p^2 = .015$). For purposes of information, the duration necessary to perform a block of putts steadily increased as the distance from the hole increased, more so for infrequent-error learners ($M = 3$ min 18 s at the distance of 25 cm to $M = 4$ min 27 s at the distance of 100 cm) than for frequent-error learners ($M = 5$ min 23 s at the distance of 150 cm to $M = 6$ min 16 s at the distance of 225 cm for frequent-error learners), as evidenced by a significant interaction between block and type of learning, $F(3, 264) = 68.79$, $p < .001$ ($\eta_p^2 = .439$).

significant three-way interaction among age group, type of transfer group, and type of learning, Wald $\chi^2 = 1.74$, $p = .188$. In sum, the number of reported statements reflecting hypothesis testing was larger in frequent-error learners than in infrequent-error learners, regardless of age group.

Transfer phase

Putting performance. Figure 2 shows the mean number of successful putts performed by younger and older adults (top and bottom panels, respectively) at the transfer distance of 125 cm in the single-task condition (i.e., control transfer groups, represented by filled symbols) or in conjunction with the attention-demanding cognitive task (i.e., experimental transfer groups, represented by unfilled symbols), along with the mean number of successful putts performed across the learning blocks (represented by dashed lines).

In the infrequent-error learning condition, the number of successful putts (averaged across the fourth learning block and the transfer block) was

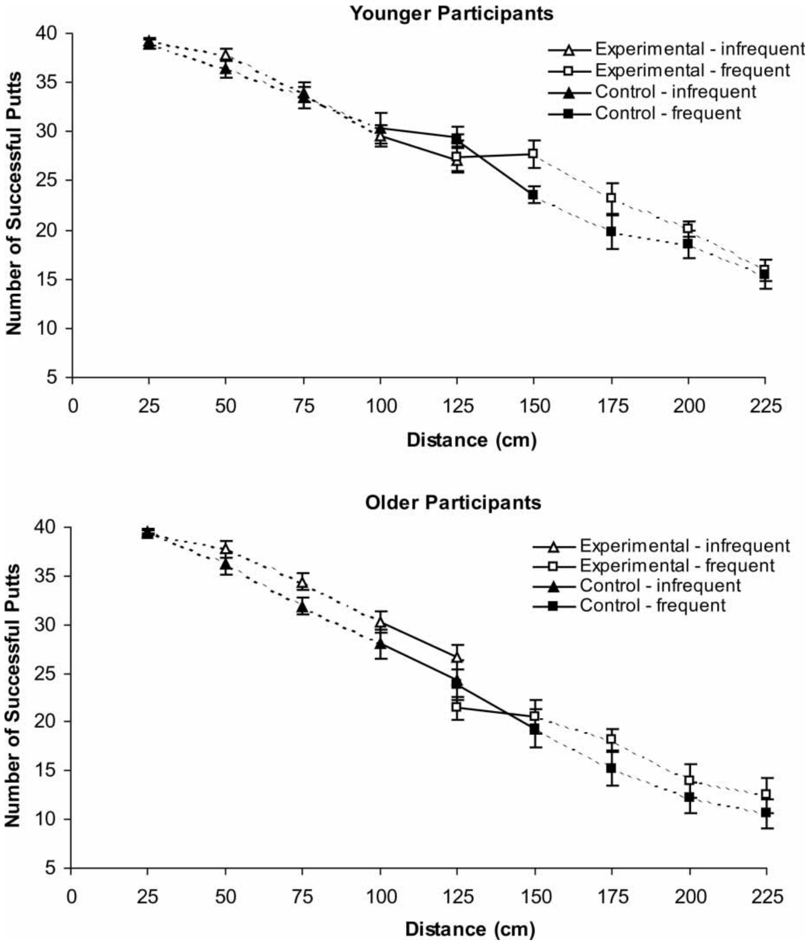

Figure 2. *Mean number of successful putts by younger and older participants as a function of distance from the hole in the learning phase (represented by dashed lines) and the transfer phase for infrequent-error and frequent-error learning conditions. Participants who performed the secondary tone-counting task while simultaneously putting (only during the transfer block) are represented by unfilled symbols (experimental transfer), and those who performed the putting task in a single-task condition (during learning and transfer blocks) are represented by filled symbols (control transfer). Bars show standard errors.*

comparable between younger adults ($M = 29.1$, $SD = 3.4$) and older adults ($M = 27.3$, $SD = 4.7$), $F(1, 44) = 2.45$, $p = .125$ ($\eta_p^2 = .053$). The main effect of type of transfer group was also not significant, $F(1, 44) < 1$ ($\eta_p^2 = .003$). The number of successful putts decreased from the training distance of 100 cm ($M = 29.6$, $SD = 4.6$) to the transfer distance of 125 cm ($M = 26.9$, $SD = 5.2$), $F(1, 44) = 12.54$, $p < .001$ ($\eta_p^2 = .222$). This decrease in performance was not influenced by the imposition of the tone-counting task, as evidenced by the absence of an interaction between type of transfer group and block, $F(1, 44) < 1$ ($\eta_p^2 = .006$). The interaction of age group and type of transfer group, $F(1, 44) = 2.80$, $p = .101$ ($\eta_p^2 = .06$), the interaction of age group and block, $F(1, 44) = 1.91$, $p = .174$ ($\eta_p^2 = .042$), and the interaction of age group, block, and type of transfer group, $F(1, 44) < 1$ ($\eta_p^2 = .007$) were not significant. In sum, the motor performance did not differ between younger and older infrequent-error learners and was not influenced by the imposition of the attention-demanding tone-counting secondary task.

In the frequent-error learning condition, the number of successful putts (averaged across the fourth learning block and the transfer block) was overall smaller in older adults ($M = 21.3$, $SD = 4.6$) than in younger adults ($M = 27.0$, $SD = 3.2$), $F(1, 44) = 24.04$, $p < .001$ ($\eta_p^2 = .353$). The main effect of type of transfer group was not significant, $F(1, 44) < 1$ ($\eta_p^2 = .002$). There was a main effect of block, $F(1, 44) = 10.06$, $p < .01$ ($\eta_p^2 = .186$), which was not influenced by age group, $F(1, 44) < 1$ ($\eta_p^2 = .001$), but was influenced by the imposition of the tone-counting task, as evidenced by the significant interaction between type of transfer group and block, $F(1, 44) = 8.25$, $p < .001$ ($\eta_p^2 = .158$). For the control transfer group, the number of successful putts increased from the training distance of 150 cm ($M = 21.5$, $SD = 5.6$) to the transfer distance of 125 cm ($M = 26.5$, $SD = 4.8$), $t(23) = 7.02$, $p < .001$. For the experimental transfer group, however, the number of successful putts was similar at the distances of 150 cm ($M = 24.2$, $SD = 6.4$) and 125 cm ($M = 24.4$, $SD = 5.7$), $t(23) < 1$. Age group did not qualify the two-way interaction between type of transfer group and block, $F(1, 44) < 1$ ($\eta_p^2 = .01$). Thus, the imposition of the tone-counting task in the transfer block affected the motor performance of frequent-error learners, but equally in the two age groups.

Accuracy on the tone-counting task. The percentage correct on the tone-counting task (which was performed concurrently with the golf-putting task only for the experimental transfer groups during the transfer block) was greater by 10.6% in younger frequent-error learners ($M = 89.2\%$, $SD = 8.8\%$, range = 73.5–98.9%) than in older frequent-error learners ($M = 78.6\%$, $SD = 9.9\%$, range = 54.7–88.4%), $t(22) = 2.79$, $p < .02$. In contrast, the percentage correct was virtually identical between younger infrequent-error learners ($M = 87.5\%$, $SD = 14.1\%$, range = 55.6–87.5%) and older infrequent-error learners ($M = 85.7\%$, $SD = 9.2\%$, range = 63.6–95.5%), $t(22) < 1$. These results suggest that older frequent-error learners either deliberately neglected the tone-counting task in favour of the motor task or were unable to comply with the instructions of being as accurate as possible on the secondary cognitive task.[3]

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[3] One may contend that motor execution of the golf-putting task was slowed by the tone-counting task for frequent-error learners, more so with age. As a consequence, the time to complete the transfer block may have been greater for older than younger adults. This hypothetical disadvantage for older adults (i.e., higher number of tones to count) may explain the observed age difference on the tone-counting task. To address this speculation, a factorial ANOVA of the time taken to complete the transfer block was carried out with age group, type of learning, and type of transfer group as between-subjects variables. Time to complete the transfer block was actually faster when the tone-counting task was simultaneously performed (4.0 min for the experimental transfer group vs. 4.8 min for the control transfer group), $F(1, 88) = 9.11$, $p < .01$ ($\eta_p^2 = .094$). The main effect of type of transfer group did not interact with either age group, $F(1, 88) < 1$ ($\eta_p^2 = .003$), or type of learning, $F(1, 88) < 1$ ($\eta_p^2 = .005$), no other effect being significant. Therefore, the age difference on the percentage correct on the cognitive task in frequent-error learners cannot be due to an age difference in the amount of time necessary to complete the transfer block, but rather probably reflects an age deficit in the ability to carry out the motor and the cognitive tasks simultaneously.

Discussion

The general goal of the present study was to examine whether motor learning is equivalent between younger and older adults in specific circumstances. The more specific goal pursued here was to identify the nature of age effects on nondeclarative, procedural, automatic memory processes, presumed to be predominantly involved in performance when few errors occurred during learning a golf-putting task. In order to achieve this, we tested the assumption that infrequent-error learning encourages the predominant use of nondeclarative, automatic memory processes in both younger and older participants, while frequent-error learning encourages the predominant use of declarative, effortful memory processes.

The frequency of errors made during learning influences the relative involvement of different memory systems

Our data provided two converging lines of evidence that the weight given to nondeclarative, procedural, automatic memory processes guiding golf-putting performance was differentially influenced by the two motor-learning situations. First, the number of declarative knowledge statements (i.e., hypotheses) reported to have been used during learning was smaller for infrequent-error learners than for frequent-error learners. Second, results from the transfer phase (at the distance of 125 cm) showed that the imposition of an attention-demanding tone-counting secondary task impaired golf-putting performance for frequent-error learners, but not for infrequent error learners (both younger and older; Figure 2). In sum, the results demonstrate that, in both younger and older participants, infrequent-error learning primarily relied on nondeclarative, automatic memory processes, whereas frequent-error learning primarily relied on declarative, effortful memory processes.

These lines of evidence highlight a reduced role of declarative, effortful memory processes in the motor-skill performance of infrequent-error learners, independent of age. Such an interpretation is well accounted for by the sequential model of skill acquisition (Anderson, 1982; Fitts, 1964; Fitts & Posner, 1967; Schneider et al., 1985) if one assumes that infrequent-error learners were able to reach the autonomous/procedural stage of learning (the amount of practice dedicated to easier versions of the golf-putting task was sufficient to allow task automatization), but not the frequent-error learners (the amount of practice dedicated to harder versions of the golf-putting task was insufficient to allow task automatization). Specifically, it may be the case that infrequent-error learners initially relied on available successful skills and strategies from the first block of learning and then practised them extensively while gradually adapting to increasing distances (thus reaching the autonomous/procedural stage). In contrast, it may be the case that, throughout the learning phase, frequent-error learners relied on effortful explicit processing and attention to refine strategies to reduce the many errors that they made. However, further research is needed to determine whether the type of procedural knowledge that is laid down early in learning by infrequent-error learners is similar to the procedural knowledge characterizing expert performance or, in contrast, is a specific type of procedural knowledge uniquely developed at the outset of learning.

Age-equivalent efficiency of nondeclarative, procedural, automatic memory processes involved in early motor learning

Our data also provided converging lines of evidence that, with age, the ability to learn a new, complex motor skill is differentially influenced by the type of memory processes that prevail. First, golf-putting performance during procedural, infrequent-error learning was equivalent between younger and older adults (Figure 1) despite age deficits on neuropsychological tests assessing attention (the Stroop Victoria and the Trail Making tests) and declarative memory functioning (short-term and working memory tests). In contrast, golf-putting performance during declarative, frequent-error learning was overall lower for older than for younger adults (Figure 1), consistent with the age differences on attention and declarative memory functioning found in the neuropsychological assessments. Second, it appeared that motor performance in declarative, frequent-error learning required more attention for older than for younger adults, as evidenced by an age deficit on the concurrent cognitive task of 10.6%. Consequently, declarative, effortful memory processes involved in motor learning were affected by advancing age. In contrast, nondeclarative, procedural memory processes involved in motor learning appeared to be preserved from normal ageing.

The age difference found on the tone-counting task in declarative, frequent-error learning is consistent with the finding that when a sensorimotor task such as walking and an attention-demanding task such as memorizing are paired together, older adults tend to prioritize the motor aspects at the expense of the cognitive aspects of the dual task (e.g., Li, Lindenberger, Freund, & Baltes, 2001; for a review, see Schäfer, Huxbold, & Lindenberger, 2006). In contrast, no age difference was observed on the tone-counting task for infrequent-error learners (87.5% for younger adults vs. 85.7% for older adults). Consequently, older adults appear to encounter more difficulties in reaching the autonomous/procedural stage of learning (i.e., difficulties to automatize aspects of a motor task) when the prevalence of errors during learning is high, but not when it is low.

Relation to the ageing literature

It is well established that advancing age differentially impairs declarative, effortful memory processes while leaving nondeclarative, procedural, automatic memory processes relatively intact (Hoyer & Verhaeghen, 2006). This conclusion has often been drawn from studies using discrete or serial cognitive tasks that minimize the perceptual and motor components of the tasks. The present results extend this view to the acquisition of complex motor skills oriented toward a goal that people are aware of (i.e., getting the ball in the hole) and that involve use of an instrument (i.e., golf club). Further research may be needed to determine to what extent the nondeclarative, procedural, automatic and declarative, effortful components of complex motor skills are comparable with those of simpler, more discrete motor skills.

Age deficits in declarative memory processes may in part be attributable to decrements in general cognitive resources with advancing age, such as attentional capacity (for a similar view but with miniature golf experts, see Molander & Bäckman, 1996; for reviews on attention and ageing, see Allen, Ruthruff, & Lien, 2007; Hartley, 1992) or processing capacity (for reviews on speed of processing and ageing, see Hartley, 2006; Salthouse, 1996). Given that declarative, effortful memory processes play a crucial role in eliminating errors during skill learning (Baddeley & Wilson, 1994), it is possible that these processes, beyond simple storage of verbal and visuospatial information, rely partly upon executive processes such as attention and inhibition, task management, planning, monitoring, and coding (Smith & Jonides, 1999; see also Hartley & Speer, 2000). Therefore, future research needs to determine whether advancing age has specific or general effects on the subcomponents of declarative memory and executive functions needed to guide complex motor skills.

Possible directions for future research

Further research is needed to more thoroughly investigate the efficacy of this age-independent method of motor learning and to determine whether our findings apply beyond the present motor task, especially to ecologically representative tasks identified as crucial for independent living (e.g., instrumental activities of daily living; Lawton & Brody, 1969). This issue is of particular interest when one considers recent evidence that highly practised natural coordination such as walking can be disrupted by conscious attempts to control and monitor limb movement in elderly repeat fallers (Wong, Masters, Maxwell, & Abernethy, 2009). The generality of the findings also remains to be established beyond the present population of independent-living older adults to individuals encountering important deficits in declarative, effortful memory processes, such as in patients suffering from Alzheimer's disease.

CONCLUSIONS

In summary, in an experiment exploring the effects of ageing on the ability to learn to perform a new motor skill (i.e., golf putting), we found age-equivalent motor performance when nondeclarative, procedural, automatic memory processes predominated but distinct age differences when declarative, effortful memory processes prevailed. These findings demonstrate that knowledge representations that do not depend on the availability of attentional resources (procedural knowledge) can be overrepresented early in motor learning, and that they are unaffected by normal ageing. Therefore, the findings suggest that learning abilities may be preserved across normal ageing and accessed at the outset of learning when the environment favours the use of procedural memory processes to guide the motor skill.

Original manuscript received 21 October 2010
Accepted revision received 21 April 2011
First published online day month year

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