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Functional aging impairs the role of feedback in motor learning

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Aim: Optimal motor skill acquisition frequently requires augmented feedback or knowledge of results (KR). However, the effect of functional declines on the benefits of KR remains to be determined. The objective of this research was to examine how cognitive and motor deficits of older adults influence the use of KR for motor skill learning.

Methods: A total of 57 older adults (mean 73.1 years; SD 4.2) received both cognitive and eye–hand coordination assessments, whereas 55 young controls (mean 25.8 years; SD 3.8) took only the eye–hand coordination test. All young and older participants learned a time-constrained arm movement through KR in three pre-KR and post-KR intervals.

Results: In the subsequent no-KR skill retests, absolute and variable time errors were not significantly reduced for the older learners who had KR during skill practice, especially for those with cognitive and motor dysfunctions. The finding suggests that KR results in no measureable improvement for older adults with cognitive and motor functional deficiencies. More importantly, for the older adults, longer post-KR intervals showed greater detrimental effects on feedback-based motor learning than shorter pauses after KR delivery.

Discussion: The findings support the hypothesis about the effects of cognitive and motor deficits on KR in motor skill learning of older adults. The dynamics of cognitive and motor aging, external feedback and internal control mechanisms collectively explain the deterioration in the sensory-motor learning of older adults. The theoretical implications and practical relevance of functional aging for motor skill learning are discussed. **Geriatr Gerontol Int 2013; 13: 849–859.**

Keywords: aging, attention, cognition, knowledge of results, motor control and learning.

Introduction

Skill learning is often influenced by the age, cognitive abilities and motor experience of the learner. The nature of the task and practice environment also affect skill acquisition.[1,2] Knowledge of results (KR), which provides feedback about the outcome of a motor skill, is a critical aspect of motor learning. KR facilitates skill acquisition if KR is provided with the right timing, precision, schedule, frequency and/or error range.[3–5] The present study tested the effect of cognitive-motor aging on KR in learning a time-constrained motor skill. KR was presented to the older and younger learners at varying intervals after practice trials (pre-KR delay) or before subsequent learning attempts (post-KR delay). The results would benefit the formation of effective motor learning and rehabilitation strategies for older adults.

Older adults often experience deficits in attention, memory, executive function, processing and motor speed.[6–10] Although studies have shown consistent KR benefits for learners at different ages, the role of attention or working memory in the use of KR for skill learning remains unclear, unless both cognitive and motor abilities are measured.[11–14] Older adults might use KR in skill acquisition at a level comparable with younger adults, the underlying processes of KR for motor learning are not fully understood.[11,13,15–17] Therefore, examining how functional declines mediate the KR effects on skill learning offers a valuable opportunity to address key issues in learning mechanisms of older adults.

Specifically, slower processing speeds in older adults could elevate motor errors with short post-KR delays (0.5, 1 and 3 s) despite a similar learning pattern for all ages.[18] However, the effect of functional declines on skill

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learning was unclear, because cognitive and motor tests were absent. The KR benefits are also task-specific and open to further examination.[19] Previous studies used spatial- or force-constraint motor tasks.[11,16,20] Exploring the role of KR in learning a temporal task can shed light on how older adults use feedback in acquiring and carrying out rhythmic or timing-demanding skills or tasks (e.g. playing musical instruments or dancing with a partner).

Importantly, how do attention, concentration and working memory contribute to the use of KR in skill learning in older adults? Aging typically results in a reduction of attention capacity.[21,22] If older adults forget KR more quickly than their younger peers,[23,24] age differences in motor learning would be more marked in the longer intervals between the learning trials and KR delivery. Alternatively, the age-related difference in using KR is a binding deficit;[25] the compromised motor learning efficiency in older adults results from their reduced ability to integrate the internal record of performance with the external feedback on a given trial.[20] The hypothesis of "the longer the KR delay, the poorer the sensory-motor integration" challenges the assertion that shorter KR delays limit the time for processing KR in motor learning.[19] The resolution of this challenge can result in a better sense of the optimal strategies for using KR in skill learning, clear theoretical and clinical relevance for the therapy of older adults.[26]

The issue here is whether KR delays, before or after KR delivery, affect motor learning in older adults. In skill practice, during the pre-KR interval, learners typically focus on proprioceptive, auditory or visual feedback of the just-completed trial. In contrast, during the post-KR period, learners likely devote more cognitive resources to evaluating the external feedback than to their internal information.[5] Nevertheless, effective attention allocation or intact working memory is essential in processing both internal and external feedback for skill acquisition. Older adults who suffer declines in attention or working memory are expected to encounter greater difficulties in processing KR during longer delays than during shorter delays, resulting in poorer skill learning.[20]

Working memory plays a critical role in processing KR during skill learning.[27,28] The executive component of working memory integrates environmental data with the learning process, updates internal models of the skill, uses strategies to correct errors and excites or inhibits the responses. If a learner selectively retains the skill-associated feedback for a longer period of time, the likelihood of developing a skill or memory representation would be greater. When KR is offered during skill acquisition, learners might direct their attention to the action outcomes and increase their awareness of the task requirements. Although older adults could learn skills implicitly or explicitly,[29] they showed deficiencies in integrating motor experiences into long-term memory; impairments in working memory or memory consolidation undermine skill learning in older adults.[9,20]

Furthermore, various pre- or post-KR delay times and the resultant demands on motor execution challenge the cognitive-motor functionality of older adults. The measures of time error (the time lag between the target time and the actual movement time) in various KR delays or intervals reflect the potential impacts of cognitive mechanisms on the function of KR in the skill learning of older adults. The measures reveal the abilities to connect KR to motor performance,[30] consolidate KR with motor memory,[9] develop an internal model before the next learning attempt[25] and control the timing of force production through different neural processes.[31]

The present study therefore addresses three questions: (i) Can older adults use KR in learning a timing task? (ii) What is the cognitive basis of KR in their learning? (iii) Are there any optimal KR intervals for their learning? To answer these inquiries, pre- and post-KR delays with 3-, 6- and 12-s intervals were used ("delay" is the timing, whereas "interval" is the time of KR). Pre-KR delay involves varying the time between the end of a trial and the succeeding KR delivery; the next trial then starts after a constant time interval. Post-KR delay involves varying the time from the KR delivery to the subsequent trial. KR is always given over a constant interval after a trial (Fig. 1). The participants explicitly learned a timing motor task through KR. Because older adults often show slower response times and compensate for their slowness by using anticipatory strategies, a fairly slow but time-stipulated arm movement was used. This design is of value in understanding cognitive aging and the use of KR in motor learning.

To understand how functional deficits of cognitive-motor aging and KR delays influence skill learning, all participants took a hand tapping test to assess their coordinative motor ability to balance movement speed and accuracy.[2] Older adults are often slower and less accurate in motor performance than young adults, showing the effects of aging on motor control. To exclude those with cognitive disorders, such as Alzheimer's disease, older adults were screened by the Mini-Mental State Exam (MMSE).[32] Furthermore, the older adults were assigned to cognitively normal or impaired groups by a usual geriatric measure (the Trail Making Test [TMT]).[33,34] Thus, the effects of functional aging on the use of KR for feedback-based motor learning could be examined. Older adults would be less accurate in timing control than young adults; KR would not help cognitively impaired older adults in improving their timing accuracy. Finally, a 3-s KR interval was expected

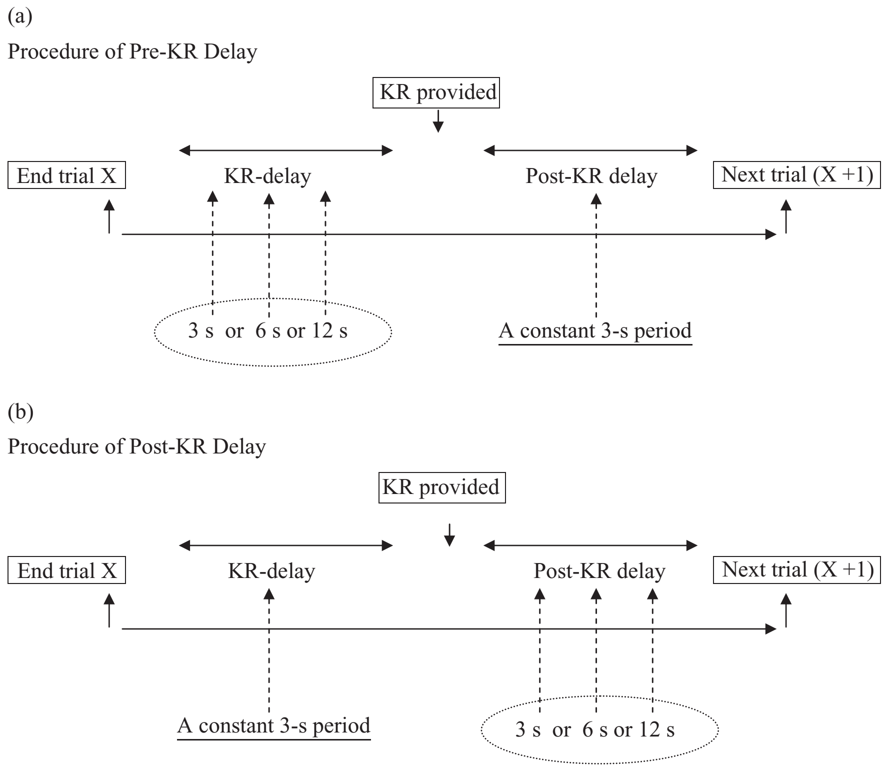


Figure 1 The procedures are shown for two experimental conditions: (a) pre-knowledge of results (KR) delay and (b) post-KR delay. In the pre-KR condition, the pre-KR delay period changed (3, 6 or 12 s), whereas the post-KR delay period was constant (3 s). In the post-KR condition, the pre-KR delay was constant (3 s), whereas the post-KR delay changed (3, 6 or 12 s). The diagram shows the sequence of events for the practice trials for these two conditions. (a) The pre-KR delay was varied with the post-KR delay held constant. After each practice trial, KR was given following a 3, 6 or 12-s delay. Then, after a constant 3-s period, the next practice attempt began. (b) The post-KR delay was varied with the pre-KR delay held constant. Each practice trial was followed by a constant 3-s delay before KR was given. The next practice attempt began after a post-KR interval of 3, 6 or 12 s. The inter-response interval is the sum of the pre- and post-KR delays (maximum of 15 s).

to be more effective than 6- and 12-s intervals for motor skill learning in older adults under both the pre- and post-KR conditions.

Methods

Participants

A total of 102 naïve volunteers gave informed consent approved by the institutional review board (Table 1: 57 older adults [OA], aged 67–76 years, 73.1 ± 4.2; 55 young adults [YA], aged 21–29 years, 25.8 ± 3.8). The Edinburgh Handedness Inventory was used to confirm the self-reported handedness of the participants (93% right dominants).[35] The OA were senior residents without identifiable cognitive disorders or potential neurological deficits (MMSE, 27–30, 28.9 ± 1.9). The YA were college students. The participants in each age group were randomly assigned to one of the pre- or post-KR experiments. In the acquisition phase, a randomly assigned subgroup in each age group received KR (KR, experimental), and the other group received no KR (CO, control). In each OA experimental group, the learners were grouped into cognitively normal (CN) or cognitively impaired (CI) by the TMT-A and -B cut-off times of 60 s and 85 s, respectively. During the retest, no KR was given for all of the participants (Table 2).

Apparatus, design and procedures

Geriatric tests

The MMSE was used to determine essential cognition. TMT-A measures visual attention by quickly connecting 25 consecutive numbers placed semi-randomly on a piece of paper in ascending order (e.g. 1-2-3-4). TMT-B assesses concentration, divided attention and mental flexibility (multi-tasking) by connecting 13 numbers and 12 letters in an alternating fashion (e.g. 1-A-2-B-3-C). TMT-B involves a rapid visual search and sequencing ability similar to those required in TMT-A, but also assesses executive functions, including the abilities to concentrate and maintain two separate trains of thought at the same time, alternating back and forth, to focus on the task and to execute and modify a plan of action. The time to complete the speed-dependent tasks is the measure of interest.

Tapping test

With a pencil, each participant repeatedly tapped two targets on a piece of paper. The circular targets were 2 cm in diameter and 6 cm apart. In each 10-s trial, once the "go" signal was given, participants made as many pencil marks as they could inside the targets on the paper. The speed and accuracy performance was recorded as the mean number of hits in three trials. The

Table 1 Demographics, cognitive and tapping tests of the participants in two knowledge of results conditions

	Pre-KR delay YA-KR ($n = 16$)	YA-CO ($n = 10$)	OA-KR† ($n = 15$)	OA-CO ($n = 10$)	Post-KR delay YA-KR ($n = 19$)	YA-CO ($n = 10$)	OA-KR ($n = 22$)	OA-CO ($n = 10$)
Age (years)								
Mean (SD)	25.7 (6.1)	26.1 (5.8)	75.9 (7.8)	76.5 (7.2)	24.7 (5.1)	25.4 (6.4)	71.1 (5.9)	70.8 (6.1)
Sex								
Female	10	6	10	7	11	7	13	6
Male	6	4	5	3	8	3	9	4
Education (years)‡								
Mean (SD)	14.6 (1.7)	14.8 (1.6)	13.5 (2.6)	13.2 (2.3)	14.8 (1.1)	14.1 (1.8)	13.7 (2.7)	12.9 (2.4)
MMSE§								
Mean (SD)	NA	NA	28.5 (1.9)	29.1 (2.2)	NA	NA	28.8 (1.3)	29.3 (2.5)
TMT-A (s)								
M (SD)	NA	NA	61.5 (3.8)	59.8 (3.6)	NA	NA	60.3 (4.1)	58.9 (3.7)
TMT-B (s)								
Mean (SD)	NA	NA	86.5 (6.2)	85.1 (7.1)	NA	NA	86.1 (6.6)	84.3 (7.5)
Average tapping speed¶ (dominant hand; ms)								
Mean (SD)	275 (28)	269 (23)	382 (42)	376 (45)	285 (31)	267 (26)	377 (38)	383 (41)

†Each of the older adults with knowledge of results (OA-KR) group was further divided into two subgroups based on the results of the Trail Making Test (TMT) Part A-B: OA-cognitively normal and OA-cognitively impaired. ‡There was a small difference between the younger and older adult cohorts because of the difficulty of recruiting older adults with equivalent levels of educations with the younger adults. §Mini-Mental State Exam (MMSE; Folstein, Folstein & McHugh, 1975). ¶Age differences between young adults (YA) and OA: KR-delay, F (2, 39) = 5.73, $P = 0.001$; Post-KR, F (2, 49) = 5.08, $P = 0.0001$, respectively. OA-CO, older adult controls without knowledge of results; OA-KR, older adults with knowledge of results; YA-CO, young adult controls without knowledge of results; YA-KR, young adults with knowledge of results.

Table 2 Age groups and subgroups of the pre- and post-knowledge of results experiments

Age	Acquisition		Retest
# Pre-KR delay			
YA ($n = 26$)	KR (experimental group, YA-KR, $n = 16$)		No KR
	No KR (control group, YA-CO, $n = 10$)		No KR
OA ($n = 25$)	KR (experimental group, OA-KR, $n = 15$)	Normal (OA-CN, $n = 8$) Impaired (OA-CI, $n = 7$)	No KR
	No KR (control group, OA-CO, $n = 10$)		No KR
# Post-KR delay			
YA ($n = 29$)	KR (experimental group, YA-KR, $n = 19$)		No KR
	No KR (control group, YA-CO, $n = 10$)		No KR
OA ($n = 32$)	KR (experimental group, OA-KR, $n = 22$)	Normal (OA-CN, 13) Impaired (OA-CI, 9)	No KR
	No KR (control group, OA-CO, $n = 10$)		No KR

KR, knowledge of results; OA, older adults; OA-CO, older adult controls without knowledge of results; OA-KR, older adults with knowledge of results; YA, young adults; YA-CO, young adult controls without knowledge of results; YA-KR, young adults with knowledge of results.

mean movement time per tap (MT = 10 s/the number of hits) was calculated. Monitored by researchers, each participant alternated tapping between targets. Multiple taps in a single target was not allowed. The tapping results captured the basic function of eye–hand coordination and confirmed that the OA group had no potential motor or neurological deficits that might affect the motor learning.

Learning experiments

A linear-slide apparatus determined the effects of pre- or post-KR delays on the timing accuracy of arm movements. The apparatus consisted of a 45-cm case-hardened steel rod mounted on two steel bases and supported by a 48-cm long and 25-cm wide wooden platform. The slide moving along the steel rod was a 5-cm steel, square ball bearing that encased the steel rod. A 15-cm handle to which a standard stopwatch was attached was mounted on the steel slide (Fig. 2). When the learner initiated the handle from the base and stopped the handle by releasing the trigger, a micro-switch was turned on or off. The timer recorded the MT between the action onsets and offsets.

The learner sat comfortably and faced the slide. With the dominant hand and over a given distance, the participants were instructed to move the handle the full length of the slide without hitting the end base to stop. No back-and-forth action was allowed. Each participant moved the hand-held lever from the start position (close to the body) to the end position (away from the body) as closely as possible to the target time of 1000 ms (Fig. 3). The participants repositioned the arm immediately after a trial.

Skill acquisition and retest were two phases in both the pre- and post-KR delays. Before the acquisition trials, all learners practised the task to understand the target time, body position and movement. No feedback

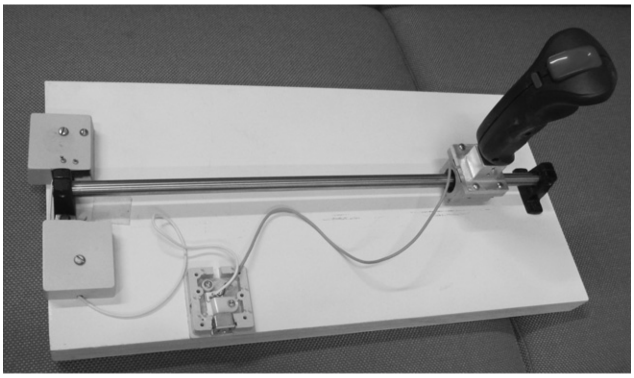


Figure 2 A linear-slide apparatus measured the timing accuracy of arm movements. The learner could move the handle from the base to the end of slide while a stopwatch recorded the movement time.

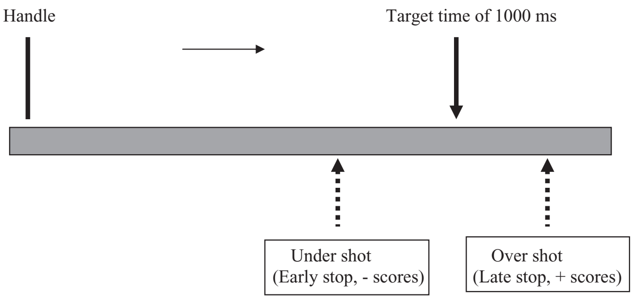


Figure 3 A graphic depiction of the linear-slide apparatus and the timing measures for the time-constrained arm movements. Each learner attempted to coordinate the temporal dynamics of an arm movement within a distance of 45 cm without specific velocity requirements. There would be no timing error if the handle moved and stopped at exactly 1000 ms. When the handle moves for less than 1000 ms, the timing error is negative ("undershot"), and if handle moves longer than 1000 ms, the timing error is positive ("overshot").

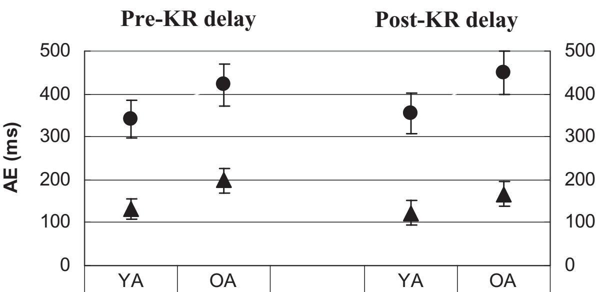
was given regarding the time accuracy of the warm-up trials. During the acquisition phase, each participant in the experimental group carried out 36 deliberate practice trials with KR (12 trials per interval for 3 intervals). Time error (rounded to the nearest 10 ms) was verbally given to the learners either as early (shorter than 1000 ms, "undershot") or late (longer than 1000 ms, "overshot"). A time error of 53 ms early (stopped at 947 ms) was presented as "50 ms early," whereas a time error of 58 ms late (stopped at 1058 ms) was "60 ms late" (Fig. 3). The participants in the control groups (CO) received no KR during the practice trials (12 trials × 3 intervals). No participants received KR while carrying out 15 retest trials (5 trials × 3 intervals). A total of 36 practice trials were used to reduce the potential impacts of fatigue or boredom on the skill learning of the older adults.

In the pre-KR delay, the learner received KR at 3, 6 or 12 s after each trial. After a constant 3-s period, the next trial began. In the post-KR delay, after a practice trial and a constant 3-s delay, KR was presented at 3, 6 or 12 s. Essentially, the pre-KR delay was varied when the post-KR delay was constant, and the pre-KR delay was constant when the post-KR delay was varied (Fig. 1). The sequence of the three intervals for each participant was counterbalanced. After the acquisition trials for a given interval, each learner carried out five retest trials. The time was recorded as either shorter or longer than the target time (a negative or positive score; Fig. 3). Retest performance was indexed in two ways: (i) absolute error (AE; ms), the overall accuracy or mean magnitude of the time error (the time difference between the target time and the actual movement time); and (ii) variable error (VE; ms), the performance consistency or variability (SD) of the time period between the target time and the actual movement time. Both AE and VE are typical timing indexes and measured the timing control ability of each younger and older participant (Note 1). The means of valid data trials were used for the statistical analyses.

Statistical analyses

The age (YA and OY), treatments (KR and no KR) and cognitive status (CN and CI) of older adults were the independent variables. The tapping speed (MT), times required to complete TMT-A and -B, AV and VE were the dependent variables. Given the sample size of 102, three interrelated sets of analyses were carried out. (i) The YA group and OA group were compared to show the aging effects on the eye–hand coordination and baseline timing control; *t*-tests examined the age differences among the MT, initial AE and VE in both experiments. (ii) The cognitive function (CN, CI) of the OA group was a between-subject factor for those in the experimental groups (Table 2); *t*-tests determined the differences between the CN and CI older learners for the times required to complete TMT-A and -B, AE and VE in the retests of both experiments. (iii) The independent variables were age (OA, YA) and treatment (KR, CO) in the pre- and post-KR experiments; each KR experiment included three distinct intervals (3, 6 and 12 s). The two experiments used a two (age) by two (KR) ANOVA. The KR interval was a within-subject factor.

For the third part of the analyses, *t*-tests were the post-hoc tests. Specifically, in the skill retests: (i) the YA group and OA group were compared to show the aging effects on learning for the three time intervals; (ii) the OA group with and without KR were compared to show the KR effects on learning while collapsing the three pre- and post-KR intervals; and (iii) the OA who differed in the TMT were compared to show the impacts of cognitive aging on the function of KR for learning while collapsing the three pre- and post-KR intervals. More importantly, to test the claim that the difficulties of OA in incorporating KR into their learning is a function of declining working memory or attention, Pearson's product moment correlations between the TMT-B scores and AE and VE were carried out. Finally, Pearson's product moment correlations between tapping speed (MT) and the arm movement duration were carried out for both the YA group and OA group. Because the pre- and post-KR experiments differed in timing manipulation, no comparisons were carried out between these two experiments. Effect sizes (η^2) are reported for all analyses. Because multiple separate analyses were carried out, the Bonferroni approach was used to prevent alpha inflation using the method of dividing the overall alpha level 0.05 by the number of analyses of five: 0.05/5 = 0.01. Coefficients (r^2) were reported for all correlations.



	YA	OA		YA	OA
● AE	340	421		354	448
▲ VE	132	198		123	167

Age

Figure 4 Age-related differences in the baseline timing control (absolute error [AE] and variable error [VE] without knowledge of results [KR]) in the pre-KR and post-KR delays. The error bars represent 95% confidence intervals for the means. OA, older adults; YA, young adults.

Results

Tapping speed and time errors

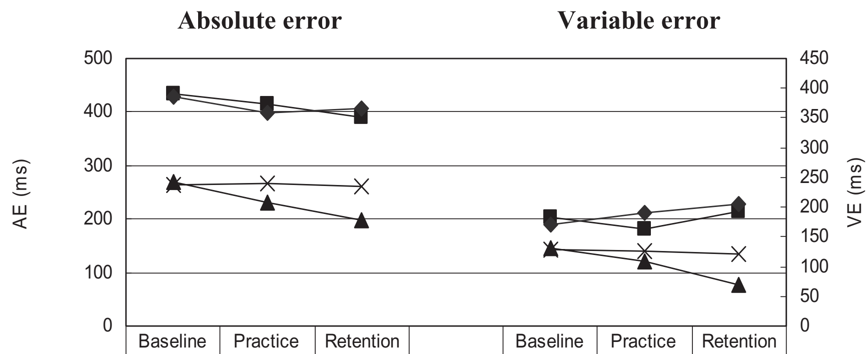
The YA group tapped significantly faster than the OA group (263 ± 23 *vs* 312 ± 29 ms), t (101) = 3.28, $P = 0.0001$, $\eta^2 = 0.45$. The OA group had significantly greater time errors (AE, VE) than the YA group in (1) pre-KR, t (50) = 12.49, $P = 0.003$, $\eta^2 = 0.78$; t (50) = 7.84, $P = 0.002$, $\eta^2 = 0.55$; (2) post-KR, t (60) = 10.78, $P = 0.001$, $\eta^2 = 0.73$; t (60) = 5.66, $P = 0.004$, $\eta^2 = 0.47$, respectively (Fig. 4). The results suggest that the younger adults outperformed the older adults in eye–hand coordination and timing control.

Effects of KR on skill learning

There were significant age by KR interactions in the retests: (1) pre-KR, F (2, 48) = 8.89, $P = 0.002$, $\eta^2 = 0.69$; (2) post-KR, F (2, 49) = 7.83, $P = 0.004$, $\eta^2 = 0.63$. KR did not reduce AE and VE for the OA, although they received KR during practice (in both KR delays, $ps > 0.01$). The YA who received KR during practice, however, significantly outperformed those who did not, t (25) = 5.81, $P = 0.014$, $\eta^2 = 0.48$ (pre-KR delay), and t (28) = 5.38, $P = 0.013$; $\eta^2 = 0.41$ (post-KR delay). The learning curves (Fig. 5) show that there were no significant differences in AE and VE reduction between the older adults who received KR and did not receive KR; for the younger adults, those in the KR group performed better than those in the no-KR group.

Effects of KR interval on skill learning

Varying pre-KR intervals did not significantly influence skill learning in all learners ($P > 0.01$). Increasing post-KR intervals, however, produced larger time errors in the OA group than in the YA group (Fig. 6). The two-way interactions of age by KR interval were



	Baseline	Practice	Retention		Baseline	Practice	Retention
—■— OA-KR	434	416	389		202	182	213
—◆— OA-No KR	428	399	406		189	212	228
—▲— YA-KR	242	208	178		132	108	69
—×— YA-No KR	237	240	236		129	126	122

Figure 5 The learning curves for the older and young adults with and without knowledge of results (KR) during the phases of baseline, acquisition and retest for the variables of AE and VE (combining pre- and post-KR delays).

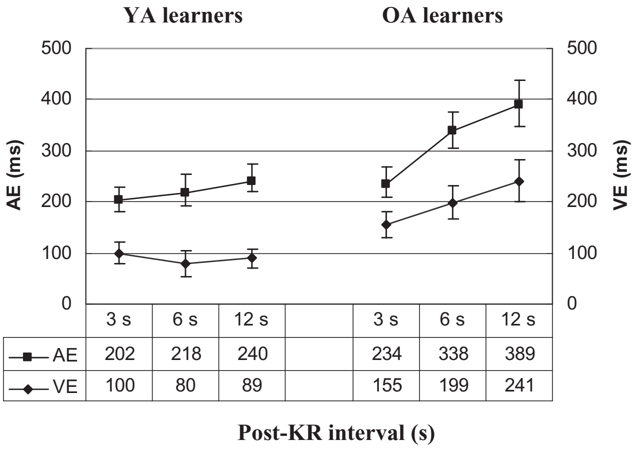


Figure 6 The impact of knowledge of results (KR) intervals on timing control (absolute error [AE] and variable error [VE]) for the older learners (OA) and young adult learners (YA) in the post-KR delay condition. The error bars represent 95% confidence intervals for the means.

significant, F (2, 48) = 5.88, $P = 0.007$, $\eta^2 = 0.42$ (AE); F (2, 48) = 3.21, $P = 0.012$, $\eta^2 = 0.37$ (VE). The OA group had greater AE (320 ± 57 ms) and VE (198 ± 27 ms) than the YA group (220 ± 39 ms; 89 ± 17 ms): t (51) = 5.27, $P = 0.012$, $\eta^2 = 0.39$ (AV); t (51) = 5.66, $P = 0.011$, $\eta^2 = 0.43$ (VE). The 3-s delay (AE, 218 ± 48 ms; VE, 127 ± 33 ms) produced less time error than the 6-s delay (AE 278 ± 44 ms, $\eta^2 = 0.42$; VE 139 ± 29 ms, $\eta^2 = 0.31$) and 12-s delays (AE 313 ± 54 ms, $\eta^2 = 0.53$; VE 165 ± 49 ms, $\eta^2 = 0.58$): t (51) = 3.24, $P = 0.013$, $\eta^2 = 0.43$ (AE); t (51) = 3.08, $P = 0.013$, $\eta^2 = 0.48$ (VE). The results suggest that post-KR intervals had minimal impacts on timing control of the younger learners; for older learners, however, longer intervals resulted in greater timing errors (AE and VE). There were differentiated effects of post-KR intervals on the younger and older learners.

Effects of cognitive and motor aging on skill learning

The cognitively normal (CN) OA were significantly faster than the cognitively impaired (CI) OA in completing TMT-A, -B and tapping (Table 3). The CN had less AE and VE than the CI in the retests (Fig. 7): for pre-KR, t (14) = 5.77, $P = 0.012$, $\eta^2 = 0.39$ (AE); t (14) = 5.79, $P = 0.014$, $\eta^2 = 0.33$ (VE); for post-KR, t (21) = 5.08, $P = 0.011$, $\eta^2 = 0.43$ (AE); t (21) = 4.97, $P = 0.013$, $\eta^2 = 0.41$ (VE). KR did not reduce AE and VE for those who had poor attention, working memory and motor abilities. In contrast, the cognitively healthy (CN) OA made significantly fewer time errors than their impaired peers (CI). The results suggest that cognitive functions of older adults affect their abilities to use KR in learning the timing tasks.

Cognitive, motor and learning parameters

The OA who had poor TMT-B scores showed greater time errors in learning (AE, r (56) = 0.42, $P = 0.012$, $r^2 = 0.18$; VE, r (56) = 0.49, $P = 0.009$, $r^2 = 0.24$). The tapping speed was not significantly related to arm movement duration (MT) in both the pre- and post-KR delays ($ps > 0.01$, $r^2 = 0.03$~0.12). The results suggest that the reduced cognitive functions of older adults reflected in TMT-A and B measures (e.g. visual attention, concentration, divided attention, mental flexibility, sequencing ability and executive functions) could result in an elevated level of timing errors in motor learning. However, tapping speed had no significant relationships with the accuracy of timing control.

Discussion

The present study examined the changes in time errors as a result of functional aging and pre- and post-KR intervals in learning a temporal motor skill. Performance was indexed as time precision relative to the goal duration. The results address three key questions: Can older adults use KR in learning a timing task? Are there any optimal KR intervals for their learning? What is the cognitive basis of KR in their learning? The magnitudes of skill improvement support the predictions of the study. The older learners with cognitive-motor dysfunctions benefited less from receiving KR than the younger and cognitively healthy older learners. The older adults in general made more time errors in the 6- or 12-s post-KR intervals than in the 3-s interval. The present study attributed the skill differences to the impaired cognitive and motor ability of older adults to utilize KR for motor learning.

The results of the cognitive and motor tests (Tables 1 and 3; Fig. 4) are consistent with past reports. Older adults often experience declines in attention, working memory, executive functions, information processing and motor speed.[7–9,23,24] The concern here was how cognitive-motor aging impairs motor learning with the use of KR for a timing task. The learning curves (Fig. 5) show that KR resulted in no measurable differences for the older learners in reducing time errors, whereas the young learners with KR performed significantly better than those without KR. Because offering KR made no significant skill improvements for the older learners, deficits in attention, concentration, working memory and motor control might in part explain the non-significant results.

Past studies have established a clear aging-related pattern of declines in cognitive and motor functions with advancing age, even in the absence of cognitive impairments.[7–9,24,26,36] Compared with young adults, older adults respond to stimuli more slowly; their movements are less smooth, less efficient and more

Table 3 Trail Making Test and tapping differences between cognitively normal and impaired older adults in the pre- and post-knowledge of results delays

Group		Part A, s (mean/SD)		Part B, s (mean/SD)		Tapping, s (mean/SD)	
Pre-KR ($n = 15$)	OA-CN ($n = 8$)	45/3.6	**	67/5.2	**	308/41	*
	OA-CI ($n = 7$)	68/4.7		91/6.5		389/43	
Post-KR ($n = 22$)	OA-CN ($n = 13$)	44/4.1	**	68/5.6	*	312/44	*
	OA-CI ($n = 9$)	70/5.2		89/7.7		387/45	

*$P < 0.05$; **$P < 0.01$, respectively. KR, knowledge of results; OA, older adults; OA-CI, older adult-cognitively impaired; OA-CN, older adults-cognitively normal.

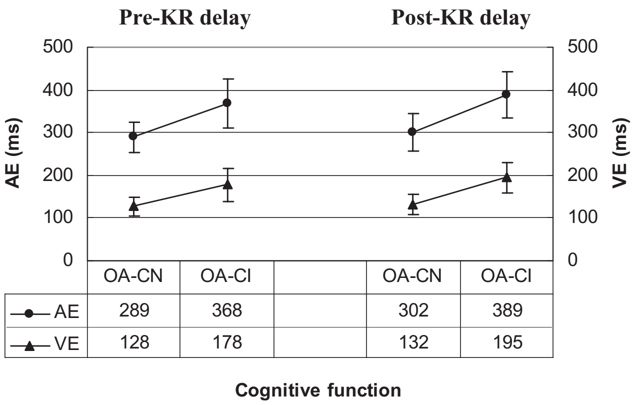


Figure 7 The differences in timing control for older learners (OA) with cognitively normal (OA-CN) and impaired (OA-CI) functioning in the pre- and post-knowledge of results (KR) conditions. The error bars represent 95% confidence intervals for the means.

variable.[8,9,36] One claim of the present study is that the age-related discrepancies in using KR for motor learning stem from the functional deteriorations in older adults. Importantly, some of the older learners suffered from attention, working memory and motor deficits (Tables 1 and 3; Fig. 4). Cognitive aging and the associated reduced motor ability contribute to the shortfall in skill learning of older adults (Fig. 7).[9]

A relevant and critical issue here was determining the optimal KR intervals for motor learning in older adults. In skill retests, the older learners had more time errors in the 6- and 12-s post-KR intervals than in the 3-s delay; the young learners showed constant time errors in the three intervals (Fig. 6). These results have critical implications for better understanding the effects of functional aging on skill learning. From a cognitive viewpoint, there are two major competing positions on the effects of cognitive aging on KR intervals for motor learning. One is that slower processing speed jeopardizes the ability of older adults to use feedback from the shorter KR delays for skill learning.[18] In contrast, the other posits that the poor attention or working memory of older adults results in their inability to sustain an on-going integration of both internal and external information. Consequently, the older adults suffer more from longer post-KR intervals than from the shorter ones.[20,25] The present results support the latter position (Figs 5–7).

The present findings that longer post-KR delays resulted in greater time errors suggest that when KR was delivered 6 or 12 s before the next trial, the older learners could not effectively use the KR to alter their motor commands. Because the KR was verbally presented to the learners, the older learners with poor attention, concentration or working memory might forget the size and direction of the error over the 6- or 12-s period. They might also forget their internal model of arm movement duration for the prolonged KR intervals, thereby reducing their ability to effectively adjust their motor commands. The older adults, however, suffered less from the longer pre-KR intervals than from those of the post-KR delay. The motor commands for the past trial likely decay, resulting in poor learning regardless of the length of the pre-KR delay.

In particular, although the older adults could use KR to adjust their motor commands for the next trial, the pre-KR intervals might not be essential for timing control. After completing a trial and before KR delivery, the older adults could focus on proprioception to plan the next trial. However, the internal representations of the past action at the perceptual level in the central nervous system are not very accurate and decay with elapsed time.[37] Once the KR was given, an older learner would switch attention from internal sources to the external KR and terminate the internal processing in a short period of time before the next trial. Consequently, the KR interrupts the ongoing internal processing during the pre-KR period, resulting in a reliance on external KR.[26]

For older learners, KR dependency might be a stereotyped response or strategies in motor skill learning. The reduced motor and cognitive abilities can contribute to the difficulties in the skill learning of older adults (Table 3; Figs 4, 7). To compensate for the motor and cognitive deficits, older adults in general would rely on KR for additional information in skill learning.[9,26] These findings are consistent with previous studies and predictions. Sensory-motor declines in attention and concentration, motor control, or reduced long- or short-term memory could in part explain the aging effects and the use of compensatory strategies in the skill learning of older adults.[7–9,24] Research needs to determine whether there is a perceptual conflict between internal and external feedback in motor learning among older adults.

Furthermore, the length of the KR interval has practical implications. This study used 3-, 6- and 12-s intervals for both KR delays. The inter-response intervals (IRI; the sum of the pre- and post-KR delays) were from 6 to 15 s. The variations in the delays were much smaller than those of Wiegand and Ramella,[18] who varied pre- and post-KR intervals from 5 to 60 s and from 0.5 to 15 s, respectively (IRI = 17.5–75 s). The correlations between the TMT-B scores and time errors support the assertion that the difficulty that older adults have in incorporating the delayed KR into their learning is a function of declined working memory or attention. Delays shorter than 3 s were not tested in the present study, and the optimal post-KR interval is uncertain. The effectiveness of a 3-s delay is relative to that of the 6- or 12-s delay. In addition, varying KR intervals did not affect the learning of young adults; 3 s is sufficient for learners to integrate sensory-motor information. Research should determine the ideal pre- and post-KR intervals for older learners.

Finally, the changing post-KR delays and subsequent demands on cognitive and motor control of older adults offer an important opportunity to examine the impact of functional aging on skill learning. The changes could hinder the abilities of the cognitively impaired to integrate KR into the internal processes of timing control in skill learning.[25,26,30] In the delayed KR conditions, older adults might be unable to update the internal representation of the skill in working memory after or before practice trials.[20,27,28] Older adults were unable to develop an internal mechanism for timing control because of poor attention, concentration or working memory (Table 3). The KR delays could also hinder the compensatory processes for older learners to adapt to a changing condition.[8,38] These results suggest that changes in KR presentation mode (an external factor) result in differences in feedback-based motor learning, reflecting the processes of internal control.[9]

As a whole, the evidence suggests that some older adults might be unable to use KR for reducing time errors because of reduced functional abilities and increased KR intervals. Changes in KR delays affect the role of KR for improving the efficiency of learning among older learners. The dynamics of the learning environments (KR delays), the skill being learned (a time-based task) and functional aging (internal control processes) collectively contribute to the observed differences between younger and older learners, between older learners with and without KR, and between older learners with and without cognitive and/or motor deficits.

Similar to the requirement of special accuracy for a skill, time or timing precision is an integral aspect of motor performance[39] (e.g. playing musical instruments, interacting with a dancing or skiing partner). Examining the relationship between the changing task demands and motor learning can facilitate future research in understanding the stereotyped motor behaviors of older adults (e.g. learning deficiency or motor variability). These efforts will facilitate the formation of effective therapy strategies for older adults who suffer from cognitive impairments (e.g. as a result of stroke or Parkinson's disease). These individuals might benefit from alternative routes of delivering KR or strengthening the KR signal by making it multisensory, more specific or clearer. Finally, understanding the neural mechanisms might enhance the assessment of the dynamic nature of KR and its contributions to learning in older adults. Obtaining more information about the role of KR in skill learning in older adults has important implications for therapy and rehabilitation.[40,41]

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Note

1 Knowing whether older adults on average overshot or undershot the prescribed time is important (e.g. constant error [CE]). Because the descriptive data showed no significant age-related patterns, no analyses were carried out on CE.

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