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Short communication

Evidence for parallel explicit and implicit sequence learning systems in older adults☆

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ABSTRACT

Some research indicates that explicit learning of a sequence can impair procedural learning, particularly in populations with reduced cognitive capacity. However, these studies usually do not distinguish the effects of explicit processes on procedural learning from their effects on performance. The current study demonstrates that explicit learning affects performance, but not procedural sequence learning, in healthy older adults even when sequences are complex. These findings support capacity-independent theories which propose that procedural and declarative learning operate in parallel.

Concurrent explicit (declarative) learning and knowledge have been found to impair procedural learning [1] particularly in instances where working memory capacity is reduced such as after stroke [2,3] or in healthy older adults [4]. One theory has posited that these implicit/explicit interactions occur because declarative and procedural sequence learning systems both compete for a common capacity-limited system [5] such as working memory [1,6]. Other theories however, posit that declarative and procedural sequence learning systems operate in parallel and do not compete for a common capacity-limited system, as long as both systems are learning the same sequence [7–9]. These latter theories suggest that evidence to the contrary reflects competition between the two learning systems at the time of performance rather than during learning [7–9].

Hence, capacity-dependent theory suggests that concurrent declarative learning should impair procedural learning, while alternate theories suggest declarative learning should not impair procedural learning, though it might affect motor performance. Most studies into explicit/implicit interactions cannot distinguish between these two theories, because they cannot separate the effects of explicit learning on procedural learning from its effects on motor performance [2,4,6,10,11]. Recent studies which have been designed to address this issue have yielded mixed results. Some indicate that when young adults are given extended training, explicit knowledge affects motor performance, but does not affect procedural sequence learning itself [8,9,12]. Other studies, also testing younger adults, suggest that when more complex sequences are used, explicit knowledge does hurt procedural sequence learning, not just performance, presumably due to competition for frontal lobe resources [1]. Consistent with this theory, some studies suggest that explicit learning has a more detrimental effect on procedural learning when cognitive capacity and working memory are reduced, such as after stroke or in healthy aging [2–4], but these studies cannot separate effects on motor performance from those on learning itself.

To provide a more sensitive test of capacity-dependent theory, the present study tested healthy older adults on a cued variant of a probabilistic motor sequencing paradigm, which required learning complex sequences and enabled effects on procedural learning to be separated from those on motor performance alone. Our earlier research using this paradigm with younger adults [12] had shown that explicit learning influenced performance but not procedural learning itself, and our goal here was to determine whether that is also the case for healthy older adults.

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Table 1
Demographic and neuropsychological information of participants.

	Incidental (n = 24)	Intentional-Without-Knowledge (n = 8)	Intentional-With-Knowledge (n = 17)
Sex (M/F)	8/16	5/3	7/10
Age	70.7 (5.1)	71.3 (6.7)	70.7 (4.7)
Education	17.3 (2.9)	16.4 (3.0)	17.6 (1.8)
Self-rated health	4.6 (0.5)	4.4 (0.7)	4.5 (0.7)
Stress score	19.7 (2.9)	20.8 (4.5)	20.4 (3.6)
Vocabulary	53.8 (6.9)	48.8 (10.8)	52.9 (7.4)
Digit span			
Forward	10.2 (2.6)	9.1 (1.4)	10.2 (1.8)
Backward	7.4 (3.1)^{a}	5.6 (1.9)^{b}	7.6 (2.3)^{a}
Digit symbol	66.5 (20.2)	52.3 (7.9)	57.7 (20.4)

Standard deviations are listed next to mean values in parentheses.
a,b = Significant group differences were found between measures of digit span backwards in Intentional-Without-Knowledge subjects (superscript b) as compared to other instruction groups (superscript a). No other significant differences were found.

The explicit/implicit Alternating Serial Response Time (eiASRT) task used here is a variant of the ASRT task from Howard and Howard [13] in which Pattern and Random events alternate, causing certain triplets of trials to occur more frequently than others. Earlier research [14] revealed that participants implicitly learn these triplet frequencies (becoming faster with practice on High than on Low frequency triplets) rather than the alternating pattern structure. This subtle regularity makes it difficult to gain explicit awareness of the pattern even with Intentional instructions [4], and so in the eiASRT, cues are used as described below to facilitate explicit learning in participants given Intentional instructions. However, when these cues are removed, explicit awareness is also removed. Therefore, blocks without cues (*Probe blocks*) provide measures of procedural learning, while *Cued blocks* show how explicit awareness affects motor performance [12].

In the present study, 50 right-handed older adults (aged 65–86 years) completed the eiASRT, though one participant was subsequently excluded because of average reaction time greater than two standard deviations above the group mean. All participants completed informed consent forms approved by the Georgetown University IRB, as well as the tests listed in Table 1.

In the eiASRT, participants press one of the four corresponding keys in response to a filled-in circle that appears in one of the four locations arranged horizontally on a computer screen. A correct response causes the circle to clear, and the next solid circle appears 120 ms later. Participants completed 3 sessions of the eiASRT in a single lab visit, with brief breaks in between. Each session consisted of three 5-block epochs. Each block contained 5 Random trials (warm-up), followed by 80 experimental trials. These 80 trials consisted of 10 repetitions of an 8-item sequence, in which Pattern trials alternated with Random trials (e.g., 1r4r3r2r where the numbers refer to positions 1, 2, 3, and 4, and "r" refers to a randomly chosen one of these four positions). Participants received one of the five possible sequences (1r2r3r4r was excluded due to possible ease of discovery). End-of-block feedback guided participants to 92% overall accuracy.

For all participants, the first two epochs of each session were *Cued epochs*, in which Pattern targets were grey and the alternating Random targets were black, whereas the last epoch was a *Probe epoch* in which all trials had black targets. Thus, epochs 1, 2, 4, 5, 7 and 8 were Cued, whereas epochs 3, 6 and 9 were Probes.

A randomly chosen half of the participants received Intentional (n = 25) and the other half Incidental (n = 24), instructions. Incidental participants were not told about the regularity; the alternating colors on the Cued epochs were explained as intended to "help participants distinguish between trials." Intentional participants were told that: "Black targets always have randomly chosen locations. However, grey targets always follow a pattern. The pattern of the grey targets repeats every four grey targets. In all blocks, in both sessions, the grey targets will follow the same 4 sequence pattern." Neither group was alerted to the regularity in the Probe epochs, although this regularity was identical to the one in the Cued epochs. During all Cued epochs (but not Probe), after each block (a total of 30 times across the experiment) Intentional participants completed a sequence report task, in which they tried to report the pattern, or to guess it if they were unsure. In Song et al. [12], all the younger adults given Intentional instructions were able to report the full correct 4-element regularity on average by the end of the third block in epoch 1 (Mean = 3 ± 2 blocks, range 1 to 10 blocks). Those given Incidental instructions gave no evidence of having gained any explicit knowledge.

In the current study, of the 25 older adults given Intentional instructions, 8 (32%) remained unable to report the full 4-unit pattern throughout ASRT testing, i.e., over 30 Cued blocks of 80 trials each (600 repetitions of the 4-unit pattern). The remaining 17 Intentional participants reported the full correct regularity on average by the end of the fifth block in epoch 1 (Mean = 5 ± 4, range 1 to 16 blocks). Based on instruction and these block-by-block sequence reports, participants were categorized into three groups: Incidental (n = 24), Intentional-With-Knowledge (n = 17), and Intentional-Without-Knowledge (n = 8). It is notable that in Table 1, the Intentional With- and Without-Knowledge groups did not differ significantly in age, education or on any other measure in the neuropsychological battery except for digit span backward (Intentional-Without-Knowledge: 5.6 ± 1.9, Intentional-With-Knowledge: 7.6 ± 2.3, $t(23) = 2.0$) which measures working memory capacity. This suggests that working memory capacity is associated with the ability to gain explicit knowledge on this task.

After completing the eiASRT, all participants were given two further tests of explicit awareness: questionnaire and card sorting. For the questionnaire, no Incidental participant reported awareness of any regularity for any epoch, whereas all Intentional participants reported that they were aware of the 4-unit alternating regularity in the Cued epochs but expressed no such awareness for the Probe epochs. For card sorting, participants were told to sort only for the Probe epochs, and participants sorted 64 cards, each containing one triplet (three trials) sequence, into two piles labeled either "occurred more often" or "occurred less often." All groups performed at chance levels when sorting High versus Low frequency triplets: Incidental, Mean = 51.6%, $t(23) = 1.4$; Intentional-Without-Knowledge, Mean = 49.6%, $t(7) = 0.45$; Intentional-With-Knowledge, Mean = 52.3%, $t(15) = 1.2$. These tests illustrate that participants, whether Intentional or Incidental, were unaware of the pattern in Probe epochs.

Hence Probe epochs assess implicit/procedural sequence learning in both Intentional and Incidental subjects. In our previous study of younger adults, reaction time and accuracy measures in Probe epochs revealed that procedural sequence learning was identical in both Intentional and Incidental learners [12], suggesting procedural learning occurred independent of explicit learning. We reasoned that if this apparent independence was occurring only because a limited capacity system needed for both forms of learning had not been taxed sufficiently in the young adults, then older adults with their more limited capacity would reveal the competition between the two learning systems, and the Intentional participants would show less learning than the Incidental participants on the Probe epochs. If instead we find equal sequence learning on the Probe epochs for all the three groups, this would suggest that procedural learning is not impaired by explicit processes even in older adults, giving stronger support to the conclusion that these

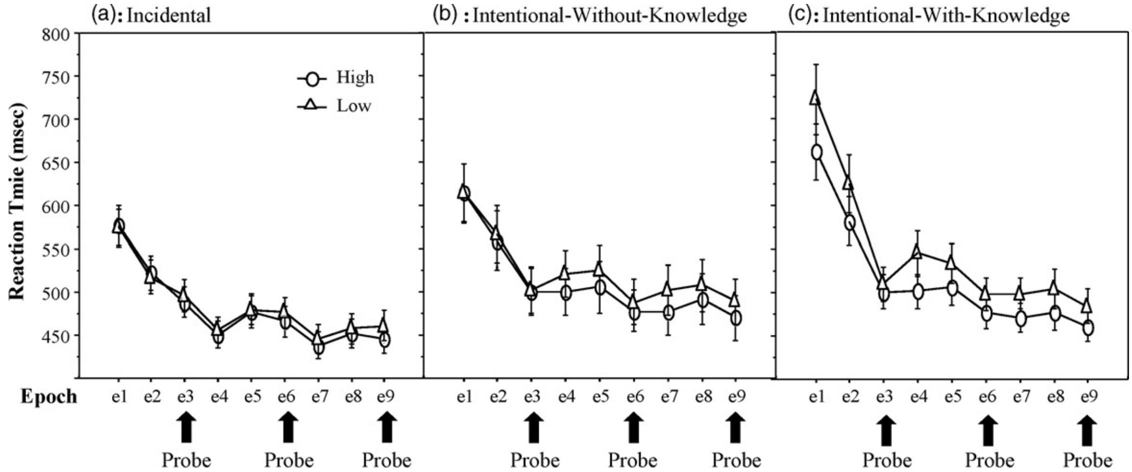

Fig. 1. Reaction time. Mean of median reaction times, split by High (circles) and Low (triangles) frequency triplets for the Incidental (a), Intentional-Without-Knowledge (b) and Intentional-With-Knowledge (c) groups. The arrows along the *x*-axis indicate the probe epochs, during which the color cues for the Intentional group were removed.

two forms of learning do not call on a common limited capacity system.

Median reaction times (for correct trials only) were determined separately for the third event of High frequency versus Low frequency triplet trials for each epoch for each participant. The means of these medians across epochs for High and Low frequency triplets are shown in Fig. 1. Triplet-type effects (RT for Low minus High frequency triplets) are shown in Fig. 2, giving a more direct picture of sequence-specific learning. The Probe epochs 3, 6, and 9 are indicated as such along the *x*-axis. As is customary with this task, for all figures and analyses in the present manuscript, triplets containing runs of three identical stimuli (e.g., 111) and those containing trills (e.g., 121) have been eliminated because of their unique properties (see, e.g., Song et al. [12]).

A $3 \times 9 \times 2$ mixed design Group (Incidental versus Intentional-With-Knowledge versus Intentional-Without-Knowledge) by Epoch (1–9) by Triplet-type (High versus Low) ANOVA of RT revealed significant main effects of Epoch, $F(8,368) = 84.70$, MSE = 2552.61, indicating general skill learning, of Triplet-type, $F(1,46) = 88.65$, MSE = 547.47, showing that High frequency triplets were faster than Low frequency ones, and a Triplet-type by Epoch interaction, $F(8,368) = 2.13$, MSE = 234.19. There was also a significant Group by Triplet-type interaction $F(2,46) = 27.12$, MSE = 547.47, a Group by Epoch interaction $F(16,368) = 5.21$, MSE = 2552.61, and a Group by Triplet-type by Epoch interaction, $F(16,368) = 4.97$, MSE = 234.19. To explore these interactions with group, we did separate analyses for Cued and for Probe epochs, because Cued epochs reveal effects of explicit search and knowledge on performance, whereas Probe epochs reflect procedural learning only.

Analyses of only Cued epochs again revealed a main effect of Triplet-type, $F(1,46) = 64.32$, MSE = 622.36, and Epoch $F(5, 230) = 94.85$, MSE = 2999.23, and there was a trend for an effect of Group, $F(2,46) = 2.81$, MSE = 94159.24. In addition, the following interactions were found: Epoch by Group, $F(10,230) = 3.81$, MSE = 2999.23, Triplet-type by group, $F(2,46) = 30.52$, MSE = 622.36, and the three-way Triplet-type by Epoch by Group, $F(10,230) = 3.35$, MSE = 282.22. Fig. 1 suggests that the Epoch by Group interaction is due to the Intentional-With-Knowledge group being slower than the other two groups initially (For epoch 1: Incidental Mean 575.6 ± 108.8 ms, Intentional-Without-Knowledge Mean 614.4 ± 93.5 ms, Incidental-With-Knowledge Mean 692.1 ± 150.9 ms). Thus, very early in training, the participants who successfully discovered the pattern explicitly responded more slowly than those who did not, suggesting strategy differences (i.e. some subjects slowed down to find the pattern). However, as mentioned previously, those unable to find the pattern explicitly also had significantly lower working memory span measures suggesting that strategy may have been partially determined by ability.

For these Cued epochs, the significant Group by Triplet-type and three-way interactions remained when any two groups were compared, and their nature can best be seen via the Triplet-type effects shown in Fig. 2. These data indicate that on Cued epochs, the three groups differed on measures of sequence learning. Fig. 1 reveals that Intentional-With-Knowledge participants show the greatest Triplet-type effect on Cued epochs, followed by Intentional-Without-Knowledge, and lastly by Incidental learners and this was especially apparent in epochs 1, 2, and 4. The advantage the Intentional-Without-Knowledge group had over Incidental learners on Cued epochs may be due to the fact that though they did not have complete knowledge of the 4-event regularity, these participants were often able to gain partial knowledge, which

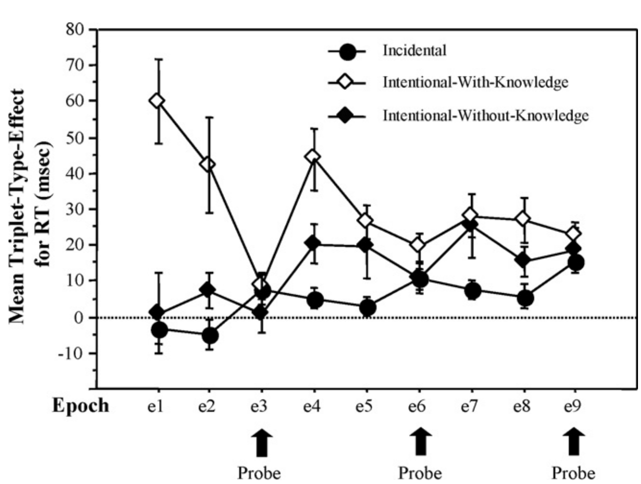

Fig. 2. Reaction time Triplet-type effect (sequence learning). A comparison of the Triplet-type effect (Low frequency minus High frequency) for the Incidental (closed circles), Intentional-Without-Knowledge (closed diamonds), and Intentional-With-Knowledge (open diamonds) groups. Differences seen during Cued epochs disappeared in the Probe epochs when the pattern was no longer cued for the Intentional groups. All groups displayed equal measures of sequence learning in Probe epochs suggesting that explicit search and/or awareness had no effect on procedural learning.

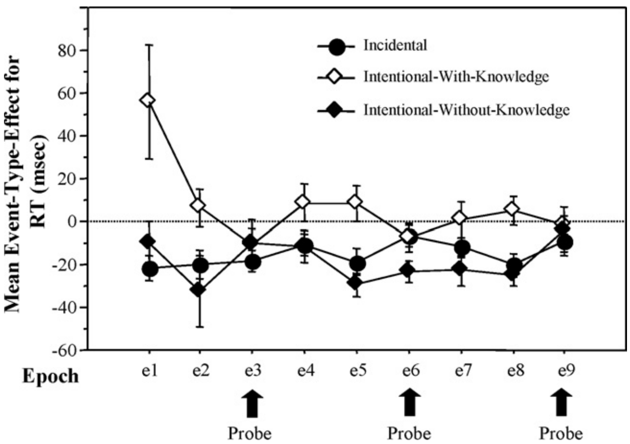

Fig. 3. Reaction time event-type effect (use of explicit knowledge). A comparison of the event-type effect (Random-high frequency minus Pattern-high frequency trials) for the Incidental (closed circles), Intentional-Without-Knowledge (closed diamonds), and Intentional-With-Knowledge (open diamonds) groups. Differences seen during Cued epochs reflect the use of explicit knowledge to affect reaction time measures. These differences disappeared in the Probe epochs when the pattern was no longer cued for the Intentional groups. These differences also decreased with training perhaps reflecting a change in strategy on the part of the Intentional group.

they could then use to increase their Triplet-type effect on Cued epochs.

For the Cued epochs, Fig. 2 reveals that Intentional-With-Knowledge participants showed less of a Triplet-type effect later in training as compared to earlier, and this may reflect changes in strategy. To examine strategy more closely, we calculated event-type effects, i.e., RT on Random-high frequency minus Pattern-high frequency trials. As explained more fully in Song et al. 2007, these reflect the use of explicit knowledge. Fig. 3 shows that this event-type effect decreased with training in Intentional-With-Knowledge subjects, consistent with the interpretation that older people relied less on explicit knowledge as training progressed. Young adults had not shown this decreased reliance with practice in our earlier study, nor had the young Intentional subjects shown the "slowing strategy" on the first few Cued epochs which the present older Intentional subjects had revealed, as discussed earlier. These qualitative age differences may represent a form of compensation on the part of older adults. The fact that the Intentional-With-Knowledge older adults adopted this "slowing strategy" on early epochs, as well as the fact that 1/3 of the older adults given Intentional instructions could not explicitly learn the pattern suggests that this task is much more difficult for older than for younger adults. This greater task difficulty for older adults may also explain why, unlike younger adults with explicit knowledge, older adults with explicit knowledge showed a decreasing effect of explicit knowledge with increased training. Because using explicit knowledge slowed down their overall reaction time, those with explicit knowledge may have changed their strategy over sessions to rely less on explicit knowledge. It is probable then that in the Cued epochs, strategy played a large role in the acquisition and utilization of explicit knowledge. This compensatory slowing and shifting in strategy may also explain why unlike younger adults, in whom use of explicit knowledge was found to hurt the expression of implicit learning early in training [12], no such correlation was found for the older adults.

For Probe epochs, which tap procedural learning, the following main effects and interactions were significant: Triplet-type, $F(1,46) = 69.16$, MSE = 140.63, Epoch, $F(2,92) = 16.06$, MSE = 1207.53, and Triplet-type by Epoch, $F(2, 92) = 7.11$, MSE = 123.44. These indicate that participants were showing both skill learning, and procedural sequence learning. Most important, for these Probe epochs, in contrast to the Cued epochs, there were no significant main effects or interactions with Group, and this remained the case when any two of the three groups were compared. Thus, these Probe epochs demonstrate that explicit search and knowledge had no effect on procedural sequence learning.

It is notable that the Intentional With- and Without-Knowledge groups did not differ in procedural sequence learning but did differ in working memory span. This dissociation suggests that working memory span influences the ability to discover the pattern explicitly, but does not affect procedural learning. This finding is consistent with Unsworth and Engle's [11] study of young adults in which working memory span was related to sequence learning only for those given Intentional instructions.

For accuracy, proportion correct for High and Low frequency triplets for all three groups is shown in Fig. 4. ANOVA revealed a significant main effect of Epoch, $F(8,368) = 9.61$, MSE = 0.002, showing that accuracy decreased over time, presumably because of the feedback directing everyone to 92% overall accuracy. In addition, Fig. 4 indicates that this decline in accuracy is primarily for Low frequency triplets, rather than High frequency triplets. Sequence learning is confirmed by a significant main effect of Triplet-type, $F(1,46) = 39.08$, MSE = 0.001, and a trend for an Epoch by Triplet-type interaction, $F(8,368) = 1.96$, MSE = 0.0005. Unlike RT, accuracy analyses yielded no main effect or interactions with Group, even

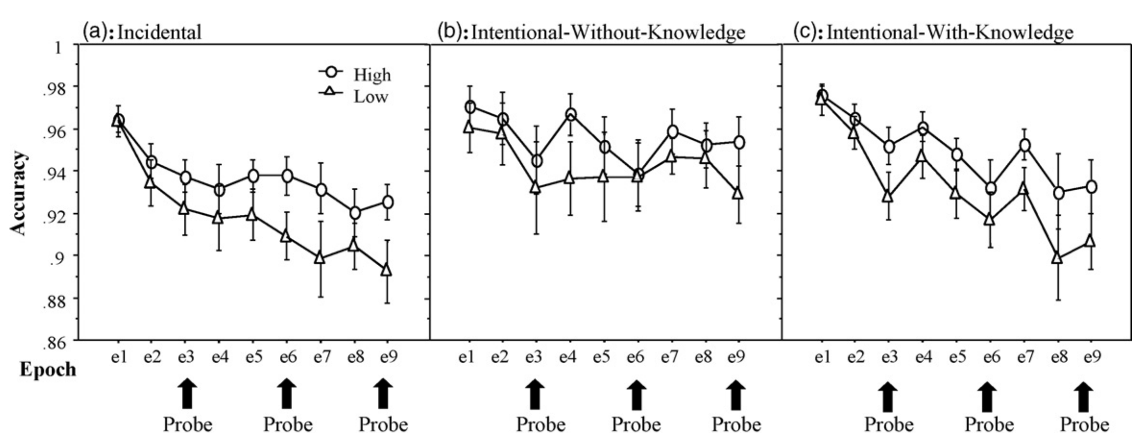

Fig. 4. Accuracy. Proportion of correct responses for the Incidental (a) and Intentional-Without-Knowledge (b) and Intentional-With-Knowledge (c) groups, split by high (circles) and low (triangles) frequency triplets. The arrows along the *x*-axis indicate the probe epochs, during which the color cues for the Intentional group were removed. No significant differences between groups were found for accuracy measures.

on Cued epochs, which had also been the case for younger adults [12].

The most important finding in the current study is that implicit/procedural sequence learning was not influenced by concurrent explicit search and learning in older adults; instructions to search for a regularity had no effect on sequence learning as measured via Probe epochs, regardless of whether the participant was successful in finding the regularity. It was not that the instructions had no effect; they did influence performance on Cued epochs. In addition, working memory was not correlated with procedural learning and performance on Probe epochs, but was related to the ability to learn the sequence explicitly and, hence, to performance on Cued epochs.

These findings provide strong evidence for a capacity-independent theory of implicit sequence learning in that neither concurrent explicit learning (Intentional-With-Knowledge group) nor unsuccessful attempts to learn explicitly (Intentional-Without-Knowledge group) impaired procedural learning, though they did affect motor performance. This was true even though the older adults were implicitly learning complex higher-order sequences (2nd order where event $n-2$ predicts event n).

The present results also suggest that earlier evidences of explicit/implicit interactions in older adults or stroke patients may have been due to the influence of explicit learning or search on motor performance, as witnessed in the present experiment in the Cued epochs, but not on learning. One study has clearly shown detrimental effects of explicit search on learning, and not just performance [1]. In this study however, very short training times were used. One possible explanation is that early in training, learning may be largely perceptual rather than motor [15] which may also explain why explicit/implicit interactions are sometimes found early in training but not later [12]. For longer training times, which are more typical for rehabilitation and skills acquired in everyday life, the present study highlights the importance of distinguishing the effects explicit learning can have on motor performance from those it can have on procedural learning itself. These are important considerations when designing and interpreting studies of motor learning and rehabilitation.

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