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Age-related differences in sequence learning: Findings from two visuo-motor sequence learning tasks

The Serial Reaction Time Task (SRTT) is thought to assess implicit learning, which seems to be preserved with age. However, the reaction time (RT) measures employed on implicit-like tasks might be too unreliable to detect individual differences. We investigated whether RT-based measures mask age effects by comparing the performance of 43 younger and 35 older adults on SRTT and an explicit-like Predictive Sequence Learning Task (PSLT). RT-based measures (difference scores and a ratio) were collected for both tasks, and accuracy was additionally measured for PSLT. We also measured fluid abilities. The RT-difference scores indicated preserved SRTT and PSLT performance with age and did not correlate with fluid abilities, while ratio RT and the accuracy-based measures indicated age-related decline and correlated with fluid abilities. Therefore, RT-difference scores might mask individual differences, which compromises the interpretation of previous studies using SRTT.

Keywords: Ageing; Sequence learning; Serial reaction time; Implicit learning; Reaction time

Introduction

The Serial Reaction Time Task (SRTT) is a visuo-motor sequence learning task commonly employed to assess the acquisition of sequential between-stimuli relations (Nissen & Bullemer, 1987; Robertson, 2007) and has been used extensively in research investigating putatively different learning systems. There are many variants of this task but, generally, participants respond to a repeating visual sequence and, after many repetitions of the sequence, random or unpredictable blocks of stimuli are introduced. Change in reaction time (i.e., RT-difference scores) is the variable of interest on SRTT, where changes in RT across successive sequence blocks or between random and sequence blocks is assumed to indicate both the presence and magnitude of sequence learning (e.g., Nissen & Bullemer 1987; Seger, 1994; Robertson, 2007).

SRTT is considered to engage and assess specifically implicit procedural learning, and the task has commonly been used in research guided by dual-systems theories of cognition. Such theories hypothesise that implicit and explicit learning (and memory) are distinct cognitive processes that draw on separate neural systems (Reber 1992; Schacter & Tulving, 1994; Seger, 1994). Implicit learning (IL) is automatic, unconscious, and remains outside of the individual's awareness, while explicit learning (EL) is conscious, often deliberate, and can be recalled or demonstrated on demand (Seger, 1994). Implicit processes are also considered to draw on evolutionarily older cognitive systems than higher-order, explicit abilities such as reasoning and working memory (Schacter & Tulving, 1994; Seger, 1994). Consistent with this, performance on IL and EL tasks tends to demonstrate dissociable relationships with other cognitive processes and abilities (Reber, 1992): Performance on IL tasks is generally unrelated to higher-order cognitive abilities and age, while performance on EL tasks tends to be positively correlated with higher-order abilities and demonstrates marked age-related declines.

Patterns in behavioural data for SRTT are consistent with those predicted by dual-systems theories for IL tasks. First, participants in SRTT studies are not informed of the presence of a sequence, and are thought to remain unaware of the between-stimuli relations as revealed by self-report awareness tests, generation tasks, recognition tests, or a combination of these (e.g., Curran, 1997; Reber & Squire, 1994; Robertson, 2007; Seger, 1994). It should be noted, however, that this view is not uncontroversial, as there have been reports that directly challenge the claim that participants remain unaware of the sequence (e.g., Perruchet & Amorim, 1992) and others argue that consciousness is a poor criterion for differentiating different types of memory (Henke, 2010; Shanks & St. John, 1994).

Second, performance on SRTT is preserved with age and dissociates with other cognitive abilities. Performance on the task is generally preserved with age when simple deterministic sequences are employed and learning is measured using RT-difference scores (e.g., Cherry & Sandler, 1995; Dennis, Howard & Howard, 2006; Gaillard, Destrebecqz, Michiels & Cleeremans, 2009; Howard & Howard, 1992; although, see Salthouse, McGuthry & Hambrick 1999). Studies that employ such variants of SRTT also tend to report that task performance is unrelated to higher-order abilities such as reasoning and working memory, but is related to speed-of-processing (PS) which is also thought to be causally prior to higher-order cognition (Kaufman et al., 2010; Reber, 1992; Salthouse et al., 1999; also see Rieckmann & Bäckman, 2009).

Also consistent with a dual-systems theory, evidence from neuroimaging studies indicates that performance on SRTT relies on the striatal memory system, whereas performance on EL tasks engages the hippocampal memory system (Rieckmann & Bäckman, 2009; Seger, 1994). The striatal system undergoes substantial age-related declines (Bäckman, Lindenberger, Li & Nyberg, 2010), which suggests that SRTT performance should decline with age. Older adults have been found to demonstrate an increased reliance on extrastriatal

regions during SRTT performance, however, and this has been taken to indicate that age preservation may be a consequence of neural compensation (see Howard & Howard 2013; Rieckmann & Bäckman, 2009).

Age-related decline on SRTT is typically observed when the to-be-learned sequence or task conditions are sufficiently complex, though it is not clear at what point such complexity becomes sufficient to produce age effects (Howard & Howard, 2013). For example, studies have reported diminished performance with age on variants of SRTT that employ complex deterministic or probabilistic sequences (e.g., Curran, 1997; Howard & Howard, 1997; also see Howard & Howard 2013). Some studies have also reported diminished SRTT performance in older compared with younger participants when task conditions are explicit (e.g., Howard & Howard, 2001) and under dual-task conditions even when the to-be-learned sequence is not overly complex (see Rieckmann & Bäckman, 2009). That age effects appear as the task becomes increasingly complex and therefore cognitively challenging has been taken to indicate that the neural mechanisms responsible for preserving the performance of older adults on simpler variants of SRTT become insufficient to compensate for reduced striatal integrity (Howard & Howard 2013; King, Fogel, Albouy & Doyon, 2013; Rieckmann & Bäckman, 2009). Moreover, PS is slowed with age, and this may also contribute to observed age-related decline on complex variants of SRTT (see Howard & Howard, 2013; King et al., 2013).

Interpreting the data from previous studies is complicated, however, by the fact that RT-based measures may have low reliability. Different types of measure are used on tasks that are assumed to assess implicit or explicit abilities, and implicit-like measures such as the RT-difference scores employed on SRTT have been found to be noisier and less reliable than explicit-like, usually accuracy-based, measures (LeBel & Paunonen, 2011; Ward, Berry & Shanks 2013a, 2013b). One consequence of this would be that relationships between

sequence learning on SRTT and both fluid abilities and age might be masked by the poorer reliability of RT-difference measures (Salthouse & Heddon 2002, p.865). For instance, Kaufman et al. (2010) calculated a binary index score with a split-half reliability of .44 and reported that SRTT performance was unrelated to fluid cognitive abilities. They argued that this level of reliability is standard for measures of IL; it was, however still low and indicates that the performance measure was noisy. Conversely, Salthouse et al. (1999) demonstrated acceptable internal consistency reliability for a sequence learning measure on a deterministic variant of SRTT ($\alpha = .74$), and they reported that learning on this task demonstrated a significant negative correlation with age and positive correlations with fluid abilities. Performance measures on two other IL tasks did not demonstrate acceptable levels of reliability ($\alpha = .40$ and $.49$), nor were they related to fluid abilities or age.

If implicit-like, RT-based measures are insufficiently reliable to detect individual differences in performance, then this could give rise to the common finding that sequence learning on deterministic variants of SRTT is preserved with age; a finding which is usually interpreted as supporting a dual-systems theory. That is, there could be a *measure reliability confound*, where RT-difference scores might be too noisy to reliably detect individual differences including age effects until they become sufficiently pronounced, such as when task conditions are particularly complex. On the other hand, if the accuracy measures that are usually employed in explicit-like tasks are more reliable, then it is more likely that they will detect individual differences, including age effects. So the *measure reliability confound* could cast doubt on the empirical evidence that is consistent with a dual-systems theory. The results of previous studies do suggest that implicit-like (RT-based) measures are less reliable than explicit-like (accuracy-based) measures in memory (Ward et al., 2013a, 2013b) and sequence learning (Urry et al., 2015) tasks, and are therefore less sensitive to individual differences.

We provide here further evidence that this is the case, focusing on age effects in sequence learning.

Urry, Burns and Baetu (2015) have previously investigated the possibility that traditional RT-difference scores might mask associations between motor sequence learning and individual differences using a Predictive Sequence Learning Task (PSLT). PSLT is a modified version of SRTT that is very similar to it but requires participants to predict, rather than react to, the location of the next stimulus. This allows the collection of meaningful RT and accuracy data from PSLT, so both implicit-like (RT-difference scores) and explicit-like (accuracy) measures can be calculated within the same task. Importantly, unlike SRTT, PSLT is an explicit-like task because of its predictive nature, and the task is similar to a generation test which has been used previously to assess explicit knowledge of sequences learnt under implicit conditions. PSLT should therefore assess EL, but Urry et al. (2015) reported that performance on PSLT appeared implicit or explicit depending on the type of measure used to assess learning. That is, RT-difference scores on PSLT were not related to fluid abilities and age, but the accuracy measures were. Urry et al. also calculated a ratio RT measure with the expectation that transforming the data might produce a more sensitive RT-based measure, and found that this behaved similarly to accuracy-based measures. These findings indicated that different types of measure are differentially sensitive to individual differences and are consistent with the *measure reliability confound* proposed above. Urry et al. could not adequately investigate age-related differences in sequence learning, however, because most of the participants were relatively young.

The current study extends the work of Urry et al. (2015) by investigating age-related differences in sequence learning in younger and older adults. We investigated whether RT-difference scores and accuracy-based measures are differentially sensitive to age effects on sequence learning across SRTT and PSLT in a within-subject design. The use of two tasks

that share a subset of performance measures provides a direct comparison of the pattern of results generated by different types of measure within PSLT, and the patterns generated by RT-based measures across PSLT and SRTT. According to a dual-systems theory of cognition, SRTT assesses IL and therefore performance on deterministic variants of the task should be unrelated to age and fluid cognitive abilities. PSLT assesses learning in an explicit manner, and so performance on this task should decline with age and correlate positively with fluid abilities regardless of how it is measured (i.e., these effects should be evident in both RT-based and accuracy-based measures, and a ratio RT measure; see Figure 1, upper panel). On the contrary, if the lack of an age effect on deterministic variants of SRTT is merely due to the fact that implicit-like measures lack reliability (*measure reliability confound*), then we would expect accuracy-based measures on PSLT to demonstrate an age-related decline which would not be detected by the RT-difference scores. That is, accuracy-based and RT-based measures would indicate diminished and preserved sequence learning with age, respectively, within the same task (see Figure 1, lower panel). We anticipated the pattern of results to be consistent with this *measure reliability confound*.

(Figure 1 about here)

Method

Participants

Participants were recruited in two age groups: Younger participants were $n = 43$ (19 women, 24 men) aged between 18 and 30 years, and older participants were $n = 35$ (12 women, 23 men) aged between 63 and 84 years (see Table 1). Mental functioning was assessed using the Standardized Mini-Mental Examination Tool (SMMSE: Molloy, Alemayehu & Roberts, 1991). All participants scored as ‘normal mental functioning’, and there was no significant group difference (Table 1). The total sample was highly educated, with the majority of

participants currently completing or having completed a university education. The number of years of education did not differ significantly between groups.

Recruitment was via advertisements posted on community websites and in local businesses, libraries, and retirement homes. Eligibility criteria were: no major medical or psychiatric conditions; no uncorrected visual disorders; not taking medications that have sedative or stimulant actions; not used any psychoactive or illicit drugs over the past six months; not suffering from drug or alcohol dependence; not smoking more than five cigarettes per day. Participants had no previous experience with the Serial Reaction Time Task (SRTT) or Predictive Sequence Learning Task (PSLT), and they were required to be native English speakers because we employed an English-language based measure of crystallized ability. Participants were paid for their time at a rate of AU\$20/hour.

Materials

Motor Sequence Learning Tasks

The sequence learning tasks were similar to the ones previously used by Baetu et al. (2015) and Urry et al. (2015). The SRTT and PSLT were matched in appearance and sequences. Both tasks comprised a 5x5 grid in which a single target square (stimulus) would illuminate at any one time, but the colour of the grids and illuminations differed between tasks so as to avoid confusion. In each task, stimuli followed one of two 8-element, hybrid sequences similar to those employed by Dennis et al. (2006). These were intended to be more complex than the sequences that have been employed previously. The current sequences used four grid locations, and each location was used twice in the sequence. There were four possible sequences counterbalanced across tasks and participants. All sequences were designed to be of similar difficulty but the grid locations that were used across the two tasks were different to minimize the effect of prior learning on the second learning task. Participants were not

informed of the sequences. Blocks 1-6, 8 and 9 were sequence blocks, comprising 10-iterations of the sequence. Block 7 was a random block in which the same four squares were illuminated as in the sequence blocks but the stimulus locations were randomly generated and not predictable, with the only constraint being that repetitions could not occur.

Participants completed both tasks, and it is possible that prior experience with the explicit-like PSLT might change performance on SRTT. Indeed, previous studies have reported that both familiarity and explicit instruction can improve performance on SRTT (e.g., Gaillard et al., 2009; Gebauer & Mackintosh, 2007). Thus, given the similarity between our two tasks and the generative-nature of the PSLT, we acted conservatively and included task order as a between-participants factor in our analyses in addition to counterbalancing the order of presentation of the tasks.

Serial reaction time task (SRTT). Participants were required to use the mouse to click on the illuminated square as quickly and accurately as possible. Illumination of a target square ceased on participant response. The inter-trial interval between participant response and the presentation of the next stimulus was 300ms. If the participant clicked on an incorrect square, a red X appeared inside it and was displayed for the duration of the inter-trial interval. If a correct response was made then only the grid of dark-coloured squares was displayed during the inter-trial interval. Reaction time (RT) was the measure of interest for this task and is the response latency between illumination of a target square and participant response. Accuracy in this task is very high and is not likely to reflect learning ability given its small variance (Urry et al., 2015).

Predictive sequence learning task (PLST). On PSLT participants were required to predict which square would illuminate next by using the mouse to click on the square of their choice. If their prediction was correct, the square illuminated and a green tick appeared inside it; if

their prediction was incorrect, the correct square illuminated and a red cross appeared inside the selected square. This feedback was presented for 300ms, after which time it ceased and participants were free to make their next selection. This task provided two types of measures – predictive accuracy measures and RT-based measures – that may reflect sequence learning. Accuracy refers to the distance (in pixels) between the center of the target square and that of the selected square, where a distance of zero indicates a correct response and a distance of 100 pixels represents the distance between the centers of two adjacent squares. RT is the length of time it takes a participant to make a response after termination of the feedback from the previous response.

Sequence learning measures

Performance measures based on RT were computed for both tasks, allowing direct comparison of performance. Learning on PSLT is also measured via accuracy, and so three additional measures were also calculated to quantify performance on this task. These measures are described below and summarized in Table 2.

(Table 2 about here)

RT-based measures. Sequence Learning on SRTT is commonly calculated as the difference in RT on a random block and either the preceding or succeeding sequence block (e.g., Cherry & Stadler, 1995; Robertson, 2007; Salthouse et al., 1999; Seger, 1994). Total Learning on SRTT, assumed to reflect both motor- and sequence-learning, has been inferred from the difference in RT on the first and last sequence blocks (e.g., Cherry & Stadler, 1995; Nissen & Bullemer 1987; Salthouse et al., 1999). We calculated both measures in the current study.

We also calculated a measure of relative improvement in RT, which quantifies learning in the form of a ratio. There appears to be little consensus as to whether such transformations

adequately address, (Reiss et al., 2006; Stevens et al., 2002) or actually exaggerate, differences (e.g., Cherry & Stadler, 1995; Gaillard et al., 2009) in RT data, especially where two groups with different baselines are being compared (see Salthouse & Hedden, 2002, pp. 867-8). Given the lack of consensus, we therefore analysed both the raw difference score measure (Sequence Learning) and the transformed score (Ratio-RT).

In order to allow a direct comparison of the RT-based measures on the two tasks, we computed these measures using all trials. This is because participants made many errors on PSLT given its predictive nature, so removing error trials would have resulted in a much larger proportion of trials being omitted for PSLT than SRTT in the early blocks, which could have biased the RT-based measures. However, some researchers have eliminated error trials when calculating RT-based performance measures on SRTT (e.g., Gaillard et al., 2009), so we also computed the three RT-based measures on SRTT using correct trials only. Given the very few errors on SRTT in the current study, those RT-based measures were almost identical to the ones computed from all trials. Accordingly, the data and analyses computed with all trials are reported here.

Accuracy-based measures. We calculated the distance (in pixels) between the selected grid location and the correct location on every trial, where an accurate prediction results in a distance from the correct location of zero. Using these accuracy data, three accuracy-based measures were calculated for PSLT: Mean Error score, Generation score, and Speed-Accuracy Trade-Off. The Mean Error score and the Generation score were both positively skewed so we normalized them by taking their inverse; this did not change the pattern of results and so we present the untransformed data. Lower Mean Error and Generation scores indicate better performance, and higher Speed-Accuracy Trade-Off scores indicate better performance.

Fluid abilities measures

Reasoning Ability was measured using a computerized short-form version of the Ravens Advanced Progressive Matrices (APM; Bors & Stokes, 1998). Working memory was assessed using the Dot Matrix, also known as Spatial Verification Span (Law, Morrin, & Pellegrino, 1995). Processing speed (PS) was assessed using two tasks: Inspection Time (IT; Vickers, Nettelbeck, & Wilson, 1972), which correlates with measures of general measures of cognitive ability (Nettelbeck, 2001); and a computerized version of the Symbol Digit Coding Task (McPherson & Burns, 2005).

Crystallized abilities measure

We included a measure of crystallized ability to demonstrate that our older sample behaved in a manner consistent with the previous literature; that is, that although their fluid abilities might be lower, their crystallized abilities should be preserved and even better than those of the young sample. This was assessed using the 34 items from the multiple-choice section of the Senior version of the Mill Hill Vocabulary Test (hereafter Word Meanings; Raven, Raven & Court, 1998).

Procedure

Participants attended one testing session that lasted approximately 90 minutes for younger participants and 120 minutes for older participants: All participants completed the same battery of tasks, but older participants generally required more time to complete the tests.

The SMMSE was administered separately to participants at the beginning of their session. Participants then provided demographic information and commenced the test battery in the order of: Word Meanings, a sequence learning task, Dot Matrix, the second sequence learning task, IT task, Symbol Digit Coding Task, and APM. An enforced 2-minute break

followed each sequence learning task and the Symbol Digit Coding Task. The order of the two sequence learning tasks (SRTT and PSLT) was determined randomly for each participant. Sixteen older participants and 24 younger participants completed the SRTT first, whereas the remaining participants completed the PSLT first (19 older and 19 younger participants).

This study was approved and carried out in accordance with recommendations by the local Human Research Ethics Committee.

Results

Demographics and Performance on Cognitive Tests

Descriptive statistics for age, education (years), SMMSE performance, and the cognitive abilities are provided in Table 1. As expected, the younger and older groups differed significantly on all cognitive abilities except the SMMSE. The older group performed better on the crystallized ability task (Word Meanings) and the younger group performed better on all fluid abilities tasks (APM, Dot Matrix, Symbol Digit, and IT).

(Table 1 about here)

Reliability estimates for performance measures

Like Ward et al. (2013b), we estimated the reliability of the performance measures on both sequence learning tasks by calculating their split-half reliability coefficients (See Table 3). The split-half coefficients were acceptable for the reaction time (RT) -based measures on both tasks, and for Mean Error score and Speed-Accuracy Tradeoff on the Predictive Sequence Learning Task (PSLT). It was not possible to calculate a split-half coefficient for the Generation score because it refers to the number of trials required to be first able to generate the entire sequence so one cannot calculate it from a subset of trials.

(Table 3 about here)

Age Effects on PSLT and SRTT Performance

Average RT and accuracy (distance from the correct location) are plotted block-by-block for each task and age group in Figure 2. Younger participants were generally faster than older participants on both tasks, and more accurate than older participants on PSLT. Accuracy on the Serial reaction Time Task (SRTT) was very high for all participants. These patterns were very similar when task order was also inspected (see middle and lower rows of panels in Figure 2).

Two-way analyses of variance (ANOVA)¹ with age group and task order (SRTT first, PSLT first) as between-participants factors were performed to investigate the effect of age and task order on performance on SRTT and PSLT according to each performance measure (plotted in Figure 3). Task order was included to assess whether the order of task presentation influenced the performance of either or both age groups. Where a significant interaction between age group and task order was found, *t*-tests were used to compare the relevant means. Additionally, where more than one pair of means were compared, the 99% confidence interval for the difference between the means was estimated via bias-corrected and accelerated bootstrapping with 10,000 replications (see Efron & Tibirishani, 1994); this is a conservative approach to correction for multiple testing because if the 99% confidence interval does not contain zero this is equivalent to adopting a *p*-value of .01 for statistical significance. If only one pair of means was compared, the corresponding 95% bootstrapped confidence interval was calculated.

(Figures 2 and 3 about here)

RT-based measures

All RT-based performance measures on SRTT and PSLT (summarized in Table 2 and plotted in the left column of panels of Figure 3) showed significant learning; that is, all were significantly greater than zero (minimum $t(77) = 6.52, p < .001$).

Sequence learning tasks are susceptible to sequential effects, which occur when the previous stimulus-response cycles affect the reaction time to a stimulus independently of learning of the sequence (Anastasopoulou & Harvey, 1999). We performed additional analyses, identical to those performed by Urry et al. (2015), to investigate some potential sequential effects that could have confounded the RT-based measures. Controlling for sequential effects did not change the pattern of results and so only the analyses calculated using the original measures are reported below.

Total Learning and Sequence Learning. None of the effects for Total Learning reached significance. There was a significant main effect of task order for Sequence Learning on SRTT [$F(1,74) = 4.75, p = .03, \eta_p^2 = .06$], and a significant interaction between age group and task order [$F(1,74) = 5.19, p = .03, \eta_p^2 = .07$]. Examination of the means (see Figure 3) revealed that the younger group performed significantly better on SRTT when it was presented second (213.3 vs 110.4 ms; $t(36) = 3.22, p = .003, d = 1.00, CI_{99} [13.8, 176.6]$). Task order did not affect the older group's performance (143.1 vs 151.3 ms; $t(32) = .22, p = .83, d = .07, CI_{99} [-106.6, 88.4]$).

Ratio-RT. On SRTT there was a main effect of age group [$F(1,74) = 10.3, p = .002, \eta_p^2 = .12$] and task order [$F(1,74) = 5.62, p = .02, \eta_p^2 = .07$]. However, there was also a significant interaction between age group and task order [$F(1,74) = 5.61, p = .02, \eta_p^2 = .07$].

Examination of the means (see Figure 3) indicated that this interaction resulted from a significant difference between the means for the younger group, where younger participants performed better on SRTT when it was presented second (.300 vs .166; $t(39) = 2.86, p = .007$,

$d = .88$, $CI_{95} [.039, .221]$). Task order had no effect on the older group ($t(32) = 0.23$, $p = .82$, $d = .08$, $95CI_{BCa} [-.098, .066]$).

There was a main effect of age group on PSLT [$F(1,74) = 11.58$, $p = .001$, $\eta_p^2 = .14$], with the younger group outperforming the older group. None of the other effects were significant.

Accuracy-based measures

There was a main effect of age on PSLT, with younger adults outperforming the older adults, for all three accuracy-based measures: Mean Error score [$F(1,74) = 39.0$, $p < .001$, $\eta_p^2 = .35$]; Generation score [$F(1,74) = 46.3$, $p < .001$, $\eta_p^2 = .38$]; and Speed-Accuracy Trade-Off [$F(1,74) = 40.3$, $p < .001$, $\eta^2 = .35$]. None of the other effects were significant.

Learning Performance and Fluid Abilities

The distribution of age across the current sample was not continuous (i.e., a middle age range was missing) and so we suggest that the magnitude of the correlations among age, cognitive abilities and learning performance reported below should be interpreted with caution.

Nonetheless, the findings reported below generally replicated the pattern of correlations reported by Urry et al. (2015) where the age range of the sample was continuous.

Correlations between RT-based measures and fluid abilities. Correlations between RT-based measures of learning and fluid abilities are presented in Table 4. As expected, Total Learning and Sequence Learning were not correlated with any fluid abilities or age on either sequence learning task.

Ratio-RT was moderately correlated with most fluid abilities measures on both tasks, with two exceptions; performance on SRTT and the IT task ($r = -.19$, $p = .105$) and performance on PSLT and APM ($r = .21$, $p = .065$) were not significantly correlated,

although both correlations were in the expected direction. Ratio-RT also demonstrated a moderate negative correlation with age on both SRTT and PSLT, indicating that performance declined with age.

(Table 4 about here)

Correlations between accuracy-based measures on PSLT and fluid abilities. Mean Error score, Generation score, and Speed-Accuracy Trade-Off had medium-to-large correlations with all fluid abilities measures (Table 5). This indicates that better reasoning ability and working memory and faster processing speed were associated with better sequence learning on PSLT. Furthermore, all three measures indicated that PSLT performance declined with age.

(Table 5 about here)

Discussion

Consistent with the results of previous studies that have investigated implicit-like and explicit-like measures (Urry et al., 2015; Ward et al., 2013a, 2013b), we found that the different types of measures detected individual differences in performance on two sequence learning tasks to different degrees. Furthermore, the pattern of results was generally similar across the Predictive Sequence Learning Task (PSLT) and Serial reaction Time Task (SRTT), despite the fact that these tasks were designed to assess explicit and implicit learning, respectively (see Table 6 for a summary of expected and actual results).

As expected, the reaction time (RT) -difference scores did not correlate with any of the fluid abilities, nor did they indicate age effects on either task. This reflects the usual pattern reported for deterministic variants of SRTT and which is predicted by a dual-systems theory, where SRTT is assumed to be an implicit learning (IL) task (e.g., Cherry & Sandler,

1995; Dennis, Howard & Howard, 2006; Gaillard, et al, 2009; Kaufman et al., 2010). On the contrary, Ratio-RT did correlate with most fluid abilities, and there was a main effect of age on both tasks (there was also an interaction between age and task order on SRTT, which we will discuss shortly). The accuracy-based measures on PSLT also correlated with all fluid abilities and detected a strong age-related decline in performance, as expected. Thus within the same task (PSLT), RT-difference scores and accuracy-based measures produced implicit-like and explicit-like patterns of results, respectively. This is more consistent with the pattern predicted by the *measure reliability confound* than a dual-systems theory (see Figure 1) and replicates the previous work of Urry et al. Furthermore, this also happened to some extent on SRTT, where the RT-difference scores produced an implicit-like pattern of results and Ratio-RT produced an explicit-like pattern of results. The latter result, in particular, is inconsistent with a dual-systems theory as it suggests that sequence learning on both SRTT and PSLT does decline with age, and that RT-difference scores are not sufficiently sensitive to detect this age effect.

The RT-based measures on SRTT and PSLT, and the accuracy-based measures on PSLT all demonstrated acceptable reliability estimates, but these were markedly lower for Sequence Learning and Ratio-RT on both tasks (see Table 3). Total Learning demonstrated excellent reliability but it is confounded with task familiarity, where the observed decrease in RT from Block 1 to Block 6 likely conflates increased task familiarity with sequence learning. The validity of this measure is therefore questionable, and this issue has been identified previously (e.g., Robertson, 2007; Salthouse et al., 1999). The more commonly used Sequence Learning measure does not suffer from this problem, and yet it demonstrated lower reliability, particularly for SRTT. Furthermore, both measures might be suffering from floor effects, which would result in smaller estimates of learning when the baseline RT is lower (e.g., in younger or faster participants; see Urry et al., 2015, for an illustration of this

effect). It is not clear, however, whether the observed insensitivity of RT-difference scores is due to reduced reliability (e.g., compared with accuracy-based measures on PSLT), validity (e.g., potential floor effects), or both. Overall, these results suggest that Ratio-RT might be more adequate than RT-difference scores to measure individual differences in learning on both SRTT and PSLT.

As explained previously, interpreting difference scores is somewhat problematic because the large differences in baseline RT between older and younger groups could mask an age effect because there is potentially a floor effect occurring in the younger group. Normalising the RT data to each individual's baseline through a log or ratio transformation is intended to address this problem and therefore produce a measure that is more sensitive to individual differences, as we observed with Ratio-RT. There is some disagreement, however, as to whether such transformations appropriately address or further obscure group differences (see Salthouse & Hedden 2002, pp. 865-870), and we caution against interpreting the findings presented in this paper as a clear indication that a ratio RT measure is necessarily an acceptable measure of sequence learning on SRTT. Rather, we intend for the reported patterns of results both within and across SRTT and PSLT to encourage further investigation into the sensitivity of (sequence) learning measures employed on implicit-like tasks. Before we conclude, we will discuss two aspects of our results that deserve further attention: the relationship between sequence learning and processing speed, and task order effects.

Correlations between learning and processing speed

The RT-based measures indicated mostly no association between performance on the sequence learning tasks and speed-of-processing (PS). This is similar to previous findings (Urry et al., 2015), but is not consistent with the usual pattern reported in the literature where performance on SRTT tends to be related to PS but not to other fluid abilities (e.g., Kaufman

et al., 2010; Rieckmann & Bäckman, 2009). According to Urry et al., a relationship between PS and learning could have been masked by floor effects, whereby individuals with higher PS also responded faster during the sequence learning tasks, which would minimize the RT-difference scores that are taken to reflect sequence learning. They found that Ratio-RT might mitigate such floor effects and did detect a relationship with PS. In the current study we also found a stronger relationship between Ratio-RT and PS compared with the RT-difference scores.

Interaction between age and task order

The results described above generally support the *measure reliability confound*, but this interpretation is complicated by the observed interaction effect between age and task-order on SRTT. Younger participants performed significantly better on SRTT according to Sequence Learning and Ratio-RT when it was presented second (i.e., when they completed PSLT first), while performance of older participants on SRTT was not affected by task order. Performance on PSLT was unaffected by task-order for both younger and older participants. This indicates that exposure to PSLT somehow benefited younger but not older participants on SRTT, but exposure to SRTT did not similarly benefit performance on PSLT for either age group.

This observed pattern cannot be well explained by the *measure reliability confound*, but it also diverges from that predicted by a dual-systems theory. This assumes that explicit learning (EL) generally does not interfere with, or may even facilitate, IL for younger adults, and that it interferes with IL for older adults due to the increased cognitive demands associated with explicit processes (Howard & Howard, 2001; Rieckmann & Bäckman, 2009). Although the performance of younger participants on SRTT improved after experience with

PSLT, the performance of older participants was unaffected, which is inconsistent with this theory.

It is possible that the observed interaction could be explained by a dual-systems theory if we take into account the age differences in magnitude of learning on PSLT. Older participants demonstrated less learning on PSLT, and so any explicit knowledge acquired on the task may not have been sufficient to impair performance on SRTT. However, this is unlikely based on the available evidence which suggests that if PSLT is truly an explicit task, then we should expect at least some transfer of explicit knowledge to SRTT which would impair performance, and the accuracy-based measures showed clear evidence of learning on PSLT in the older group.

The observed interaction may thus be better explained by differential acquisition and transfer of metacognitive skill from PSLT to SRTT. Current metacognitive models indicate that the development of pre-conscious metacognitive skill precedes that of conscious metacognitive knowledge (e.g., Sangster Jokić & Whitebread, 2014), and there is evidence that metacognitive skill may be transferred positively or negatively between sequences (e.g., Obayashi, 2004; Shimizu, Wu & Knowlton, 2016). That is, motor learning on one sequence may facilitate or hinder performance on another sequence, even in the absence of conscious knowledge about those sequences. Importantly, whether transfer is positive or negative, or occurs at all, might be a result of the conditions of practice during initial learning and individual differences including age (Obayashi, 2004; Shimizu et al., 2016). In the current study, younger participants may have acquired metacognitive skill on PSLT that facilitated their performance on SRTT, where the generative nature of PSLT (conditions of practice) was more conducive to the acquisition and positive transfer of such skill. Further, the cerebellum is thought to be involved in the positive transfer of metacognitive skill (Obayashi, 2004; Shimizu et al., 2016) but is also degraded with age (Bernard & Seidler, 2014). This

could account for the observation that the performance of older participants on SRTT was not affected by prior completion of PSLT. That is, even if older adults had acquired metacognitive skill on PSLT, this did not positively transfer and benefit their performance on SRTT.

Conclusions

The findings reported here suggest that sequence learning on deterministic variants of SRTT does decline with age and is related to fluid abilities. Moreover, the RT-difference scores commonly employed on SRTT were unable to reveal individual differences including age effects on either SRTT or PSLT. Much of the empirical support for dual-systems theories has been drawn from consistent reports of preservation of implicit learning with age and dissociation of implicit and explicit abilities. The current findings therefore cast doubt on the validity of this ‘implicit pattern’ within the SRTT paradigm; however, these findings do not necessarily challenge the assumption that SRTT engages implicit processes. Taken together with the observed interaction effect between age group and task order that also could not be well explained by a dual-systems theory, these findings lean instead toward a single-system framework that accommodates both implicit and explicit, or pre-conscious and conscious, processes (Berry, Shanks & Hanson, 2008; Keren & Shul, 2009). Further investigation into the sensitivity of RT-based measures employed on implicit-like tasks, including the RT-difference scores investigated here, is clearly warranted.

Finally, the tasks presented here may be useful in exploring further the cognitive system(s) underlying sequence learning because they are directly comparable in terms of stimuli, response requirements, and performance measures. Unlike previous studies that have compared implicit and explicit learning processes using tasks that were similar but differed in either design or performance measure (e.g., Kaufman et al., 2010; Reber, Walkenfeld &

Hernstadt, 1991; Ward et al., 2013a; although see Gebauer & Mackintosh, 2007; Howard, Howard, Dennis & Kelly, 2008; Seaman et al., 2013), the SRTT and PSLT have the same stimulus and response requirements, and the same performance measures can be used to assess learning in both tasks. Therefore, these tasks could be useful tools for investigating the cognitive system(s) involved in sequence learning.

Footnotes

¹ We also ran omnibus analyses of variance (ANOVA) that included the two sequence learning tasks as a within subjects factor. The relevant interactions were significant, and so we present the individual ANOVAs for each sequence learning task for ease of reporting and interpretation.

Disclosure of interest

The authors report no conflicts of interest.

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Table 1: Descriptive statistics for cognitive abilities

Variable	Younger participants		Older participants		Welch <i>t</i> -test		Cohen's <i>d</i>
	<i>(n = 43)</i>		<i>(n = 35)</i>		<i>t</i> (df)	<i>p</i>	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
Age (years)	22.6	3.47	70.9	5.01	- ^a		- ^a
Education (years)	14.4	2.56	15.7	3.75	1.73 (57.9)	.09	0.40
SMMSE	29.3	0.95	29.2	0.87	.27 (75.0)	.79	0.06
Word Meanings	19.3	3.95	25.4	4.91	5.93 (65.2)	< .001	1.38
APM	6.70	3.07	4.06	2.46	4.21 (76.0)	< .001	0.95
Dot Matrix	38.1	9.59	22.2	9.75	7.23 (72.3)	< .001	1.65
Symbol Digit ^b	92.6	16.5	54.2	7.28	13.6 (61.2)	.001	3.01
IT (ms) ^b	54.2	29.6	83.9	23.3	3.45 (67.9)	< .001	1.12

Notes. The Welch *t*-test does not assume equal variances in the populations; we used the same procedure in calculating Cohen's *d*. SMMSE is Standardized Mini-Mental State Examination score; APM is Advanced progressive matrices; Symbol Digit is symbol digit coding task; IT is inspection time task. Scores are number correct for Word Meanings, APM, Dot Matrix and Symbol Digit, and time in milliseconds for IT. Lower

IT scores indicate faster Processing Speed. ^a It is not appropriate to report these statistics for age because participants were recruited into two groups whose age ranges do not overlap. ^b Data were missing on IT for the younger ($n = 42$) and older ($n = 32$) groups, and on Symbol Digit for the older group ($n = 32$).

Table 2: Summary of performance measures

Measure	Description	SRTT	PSLT
Total Learning	RT Block 1 – RT Block 6	✓	✓
Sequence Learning	RT Block 7 – RT Block 8	✓	✓
Ratio-RT	$(\text{RT Block 7} - \text{RT Block 8}) / \text{RT Block 7}$	✓	✓
Mean Error score	Mean distance between the clicked and the correct locations in all sequence blocks	✗	✓
Generation score	Number of learning trials required before being able to generate the entire sequence correctly	✗	✓
Speed-accuracy trade-off	$1 / (\text{Mean Error score} * \text{Mean RT in all sequence blocks})$	✗	✓

Table 3. Split-half coefficients for performance measures on SRTT and PSLT

Performance Measures	SRTT	PSLT
Total Learning	.93	.96
Sequence Learning	.68	.83
Ratio-RT	.79	.82
Mean Error score	-	.99
Speed-Accuracy Tradeoff	-	.95

Table 4. Correlations between RT-based measures and fluid abilities, and mean and SD for all RT-based measures

Fluid abilities measures and age	Serial Reaction Time Task (SRTT)			Predictive Sequence Learning Task (PSLT)		
	Sequence	Learning	Total Learning	Ratio-RT	Learning	Total Learning
Age	-.01	-.07	* -.28	-.12	-.18	**-.37
APM	.11	.10	** .30	.04	.01	.21
Dot Matrix	.21	.05	** .38	.14	.19	** .33
Symbol Digit	.04	.20	** .30	.11	.05	** .37
IT	-.01	-.06	-.19	-.13	-.16	* -.23

Notes. Sequence Learning, Total Learning and Ratio-RT are RT-based measures of performance on the sequence learning tasks; APM is advanced progressive matrices; Symbol Digit is symbol digit coding task; IT is inspection time task. * $p < .05$, ** $p < .01$. Smaller Inspection Time scores indicate higher Processing Speed.

Table 5: Correlations between accuracy-based measures on PSLT and fluid abilities, and mean and SD for accuracy-based measures

Fluid abilities measures and age	Mean Error score	Generation score	Speed/Accuracy Trade-off
Age	** .57	** .60	**-.59
APM	**-.47	**-.44	** .55
Dot Matrix	**-.57	**-.59	** .61
Symbol Digit	**-.56	**-.57	** .65
Inspection Time	** .37	** .35	**-.39

Notes. Generation score, Mean Error score and Speed/Accuracy Trade-Off are accuracy-based measures of performance on the Predictive Sequence Learning Task; APM is advanced progressive matrices; Symbol Digit is symbol digit coding task; IT is inspection time task.

** $p < .01$. Smaller Generation and Mean Error scores indicate better performance on PSLT, and smaller Inspection Time scores indicate higher Processing Speed.

Table 6: Expected and actual patterns of results

	Expected results				Results			
	Dual-systems theory		Measure reliability confound		Main effect of age		Number of significant correlations with fluid abilities	
	SRTT	PSLT	SRTT	PSLT	SRTT	PSLT	SRTT	PSLT
Total	✗	✓	✗	✗	✗	✗	0/4	0/4
Learning Sequence Learning	✗	✓	✗	✗	*✗	✗	0/4	0/4
Ratio-RT	✗	✓	✓	✓	*✓	✓	3/4	3/4
Mean Error score		✓		✓		✓		4/4
Generation score		✓		✓		✓		4/4
Speed-Accuracy Tradeoff		✓		✓		✓		4/4

Notes. ✗ indicates that no age effect or significant correlations with fluid abilities were expected or found. ✓ indicates that a significant main effect of age or significant correlations with fluid abilities were expected or found. * indicates a significant interaction between age group and task order.

Figure Captions

Figure 1. Illustration of the pattern of results generated by a dual-system theory and the measure reliability confound.

Figure 2. Average reaction time (left panels) and accuracy (Mean Error score, i.e., mean distance from the correct location; right panels) for each block. PSLT is Predictive Sequence Learning Task; SRTT is Serial Reaction Time Task. Data is shown for all participants (upper panels), and separately for those who experienced PSLT first (middle panels) or SRTT first (lower panels). Note that the stimuli were presented in random order in Block 7. Mean Error scores for SRTT were not analysed since accuracy was very high for all participants.

Figure 3. Reaction time and accuracy -based measures derived from SRTT and PSLT. Data is presented separately for all older/younger participants (labelled 'All participants'), for those who experienced the task first ('First task'), and for those who experienced the task second ('Second task').

Figure 1

Expected pattern of results based on each hypothesis

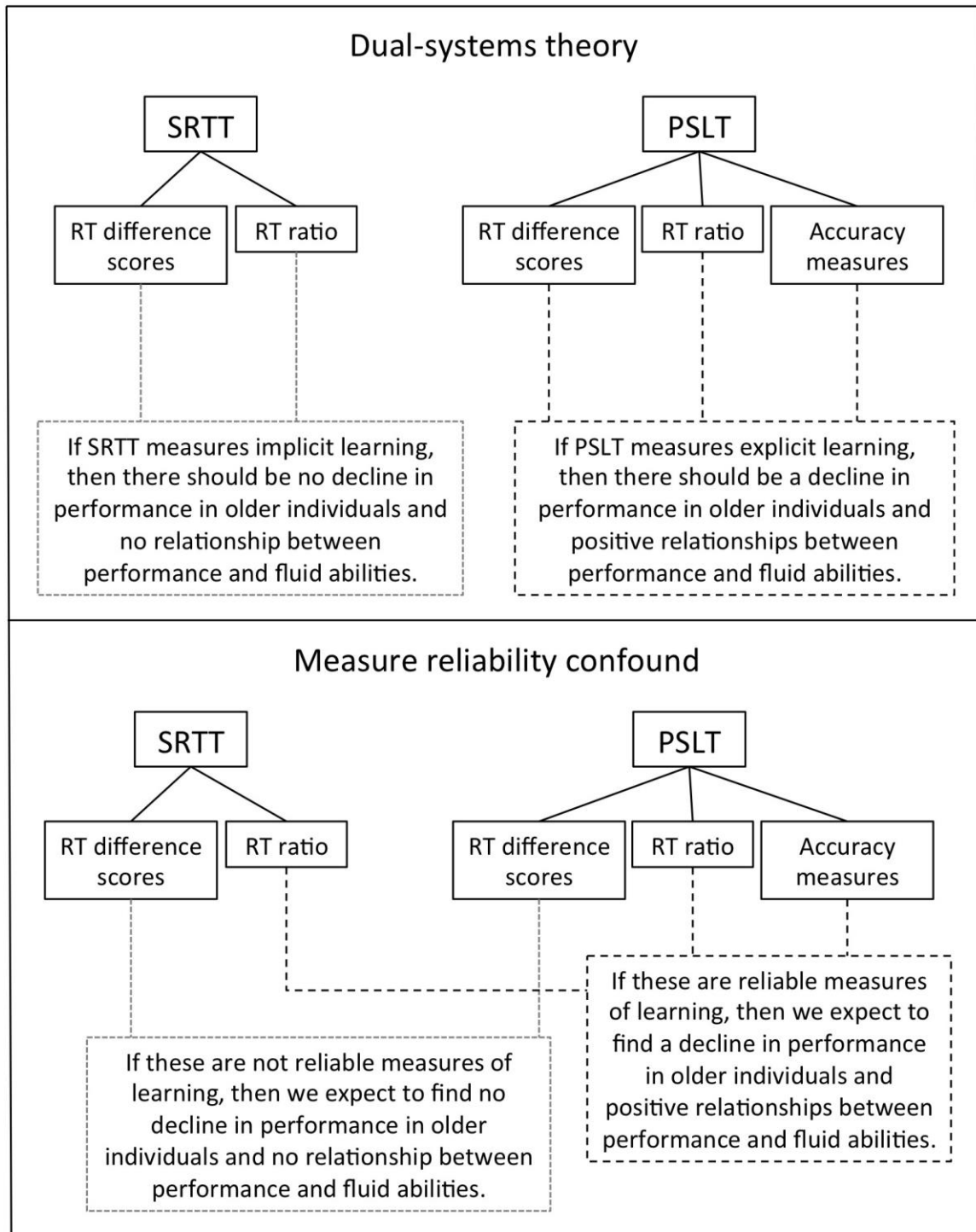


Figure 2

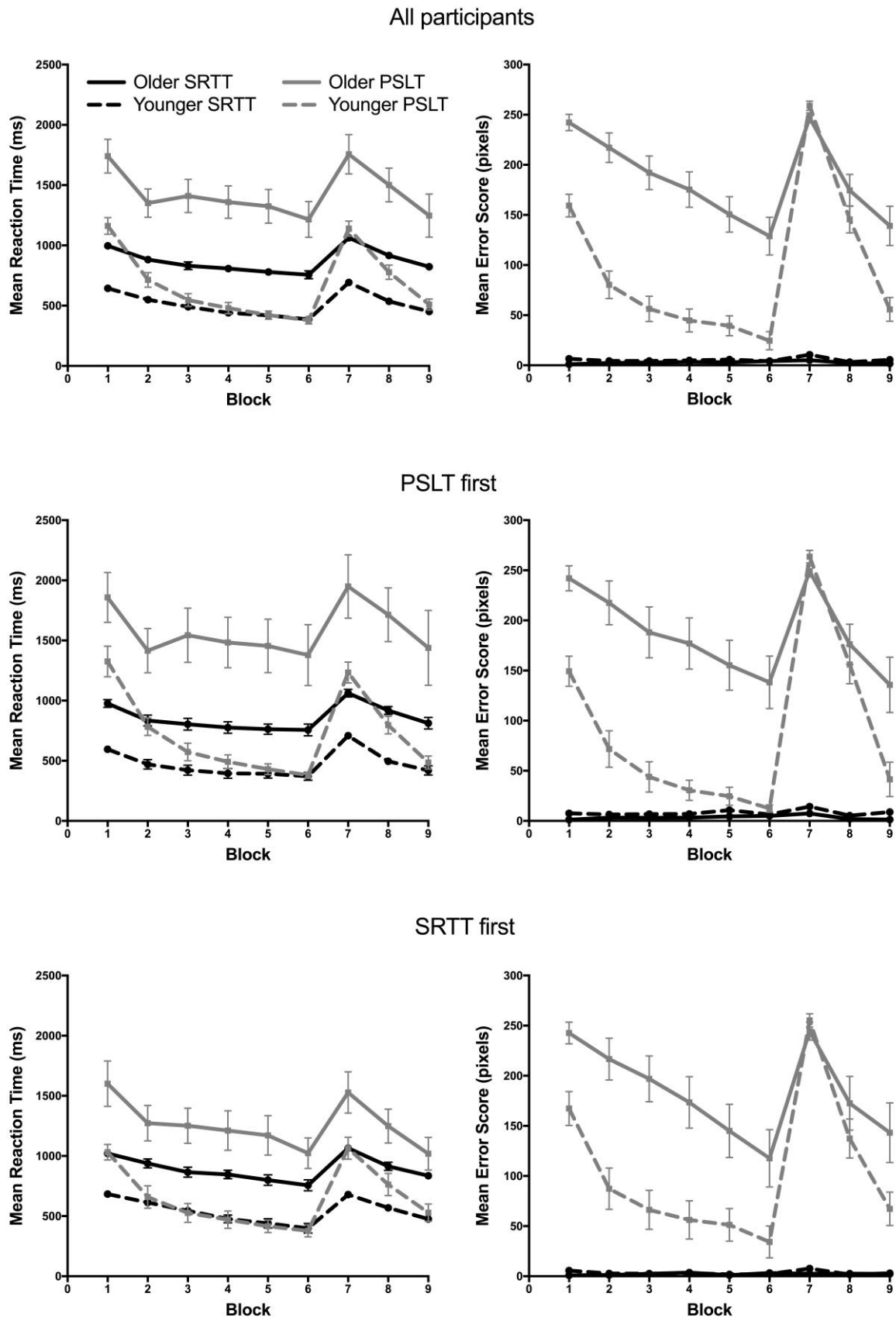


Figure 3

