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Sequential difficulty effects in cognitive and sensorimotor tasks: Insights from arithmetic and Fitts' task

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Abstract

The present study tested sequential difficulty effects (SDEs) in arithmetic problem solving and Fitts' aiming task for the same individuals. SDEs refer to poorer performance on current items following harder items relative to after easier items. Young and older adults accomplished a computational estimation task (i.e., finding the approximate products to two-digit multiplication problems) and a Fitts aiming task (i.e., performing rapid pointing movements to reach the finish areas). Current items were preceded by two easy or difficult items (i.e., in the repeated-precursor condition) or only one easy or difficult item (i.e., in the unrepeated-precursor condition). Participants' performance revealed SDEs in both the arithmetic and the aiming tasks only when the precursor items were repeated. Data also revealed comparable SDEs in both age groups during the arithmetic task, but SDEs only in older adults while participants accomplished the aiming task. These findings have a number of implications for our understanding of mechanisms underlying SDEs and age-related differences in SDEs, as they suggest that SDEs involve both domain-general and domain-specific mechanisms that are differentially influenced by aging.

KEYWORDS: aging, strategies, arithmetic, Fitts' task, sequential effects

The present study aimed to investigate how sequential difficulty effects (SDEs) change with aging and whether SDEs occur within a group of people performing different cognitive and sensorimotor tasks. SDEs refer to participants' poorer performance observed on current items that follow harder items compared with items that follow easier items. Interestingly, SDEs capture the fact that cognitive or sensorimotor performance on a current item not only depends on that item's characteristics but is also influenced by the characteristics of immediately preceding items. In previous studies, SDEs have been tested in different cognitive and sensorimotor tasks, but have never been demonstrated within a group of the same participants across different domains. In the present study, we investigated SDEs in a cognitive and a sensorimotor task to further our understanding of the mechanisms underlying SDEs. We also tested how SDEs change with aging.

Previous research described SDEs in several cognitive domains (see Mozer, Kinoshita, & Shettel, 2007, for a review), included including arithmetic problem solving (Schneider & Anderson, 2010; Uittenhove, Burger, Taconnat, & Lemaire, 2015; Uittenhove & Lemaire, 2012, 2013a, 2013b; Uittenhove, Poletti, Dufau, & Lemaire, et al., 2013, 2015) and sensorimotor tasks (Poletti, Sleimen-Malkoun, Lemaire, & Temprado, 2016), investigated here. For example, in arithmetic tasks, Schneider and Anderson (2010) found that participants verifying arithmetic problems (e.g., 17 + 42 = 59) was slowed downperformed more slowly after difficult problems (e.g., 28 + 56) relative to than after easier problems (e.g., 31 + 27). In the word-naming literature, Taylor and Lupker (2001) found that the slowdown on easy stimuli is contingent upon on the presentation of difficult stimuli on in the immediately preceding trials. In another study, Lupker, Kinoshita, Coltheart, and Taylor (2003) wanted to determine if whether sequential dependencies arise in repeatedly naming the sums. They showed that performance depends on both on the stimulus type (i.e., easy or hard items) and the composition of the block. Participants were slower (and more accurate) on easy items and faster (but less accurate) on harder items when items were presented in a mixed block (e.g., easy and hard addition problems) relative tothan when they were presented in a pure block (e.g., either only easy or difficult addition problems). Recently, Poletti et al. (2016) tested age-related changes in SDEs when participants had to perform a sensorimotor task. Using the Fitts aiming task, they found that reaching a given area was slowed downslower after reaching smaller (harder) areas relative tothan after reaching larger (easier) areas.

SDEs have been accounted for by assuming lesser availability of executive resources after more difficult items. Specifically, difficult items are hypothesized to temporarily consume more central resources (e.g., executive functions) than easier ones, thus slowing down performance on the next item (e.g., Schneider & Anderson, 2010; Uittenhove & Lemaire, 2012). One of the aims of the present study was to test whether SDEs increase with aging, presumably as a result of the depletion of information processing speed and executive resources. Additionally, it is still unknown whether SDEs and their possible changes with aging involve domain-general mechanisms (predicting that individuals people with larger SDEs in one domain would also have larger SDEs in another domain), domain-specific mechanisms (predicting that different individuals people show SDEs of different magnitudes in different domains), or both domain-general and domain-specific mechanisms (predicting SDEs in different domains for the same individuals, participants but uncorrelated SDEs across different domains). Based on previous findings of age-related increase in correlations between cognitive and sensorimotor performance (e.g., Anstey, Lord, & Williams, 1997; Anstey & Smith, 1999; Li, Aggen, Nesselroade, & Baltes, 2001; see Schäfer, Huxhold, & Lindenberger, 2006, for a review), it could be predicted that as individuals people grow older, larger SDEs in one domain will be accompanied by larger SDEs in another domain. This prediction was tested in the present study.

Another goal of the present experiment was to determine whether SDEs cumulates across items in both arithmetic and aiming tasks. Indeed, several studies investigated sequential effects in response times and showed a complex pattern extending over trials (e.g., Jones, Cho, Nystrom, Cohen, & Braver, et al., 2002; Jones, Curran, Mozer, & Wilder, 2013; Soetens, Boer, & Hueting, 1985). Moreover, both these extensions of cross-task and cumulative sequential effects have been recently investigated in another set of studies testing for SDEs across three tasks. Meriwether (2016) showed that depending on the tasks to be performed, detrimental or even facilitating effects associated with the difficulty of the previous items can be found. These effects also appear to be even larger when the difficult item sequences preceding the target item are long. Other studies (e.g., Schneider & Anderson, 2010; Uittenhove & Lemaire, 2012) have established that SDEs occurred across two- successive items (i.e., with a single precursor item before the target item) when the difficulty of the precursor and target items was similar (i.e., repetition trials) and/or when the difficulty of the precursor and target items was different (i.e., alternation trials).

Here, we tested the possibility that SDEs cumulate and increase across three- successive items (i.e., with a repeated-precursor item before the target item), or whether SDEs are of comparable magnitudes when participants see one or two precursor items. Consistent with our previous studies of SDEs, we compared performance on target items following easier items versus with performance after harder items. In both cases, SDEs were investigated here with difficulty of items alternating between precursor and target items, without asking whether sequential difficulty influences (strategy or task) switch costs. This method was expected to shed further light on how the resource depletion mechanisms, assumed to underlie SDEs, work during both cognitive and sensorimotor tasks in which participants complete several items in succession. Increased SDEs with repeated-precursor items relative to unrepeated-precursor items may be more likely found in older than in younger adults as because processing resources are known to decrease with aging (e.g., Craik & Salthouse, 2008; Glisky, 2007). Moreover, by testing repeated- versus unrepeated-precursor items, we aimed at testing more strongly than in our previous study testing whether aging has an impact on SDEs.

To achieve these goals, we asked young and older participants to accomplish a computational estimation task (i.e., finding the approximate products of two-digit multiplication problems) and a Fitts aiming task (i.e., performing rapid pointing movements to reach finish areas). Then, we compared participants' performance on current items following difficult problems (for the arithmetic task) or smaller finish areas (for the aiming task) relative to with performance on items after easier problems or larger finish areas. Moreover, SDEs were compared when precursor items were repeated or not. Of interest were whether individuals participants showing larger SDEs in one domain were those who would also show larger SDEs in the other domain, how SDEs changed with adults' age, and whether young and older adults' SDEs would differ when precursor items were repeated or not in each of the cognitive and sensorimotor domains tested here.

Method

Participants

Thirty-eight healthy volunteers, divided into two age groups, were tested: 19 young and 19 older adults (see Table 1 for participant characteristics). Young adults were undergraduates from Aix-Marseille University (Marseille, France). Older adults were recruited from the community of Marseille. They all had scores higher than 27 in the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975). First, a presentation of the experiment was provided to each participant who was then asked to sign an informed written consent, approved by the local ethic committee of Aix-Marseille University, and in accordance with the ethical standards laid down in the Declaration of Helsinki. Then, participants were individually tested in two different tasks, the arithmetic task, which consisted of estimating multiplication problems and the aiming task, which consisted of performing rapid pointing movements. The order of presentation of both tasks was counterbalanced between participants. First, all participants performed the experimental tasks (i.e., arithmetic and aiming tasks). Then, they completed a French version of the Mill-Hill Vocabulary Scale (MHVS; Deltour, 1993; Raven, 1951) to assess their verbal fluency, the addition, subtraction, and multiplication subtests of the French Kit (French, Ekstrom, & Price, 1963) to assess their arithmetic fluency with an independent paper-and-pencil test. As often found, older adults' arithmetic fluencies were greater than young adults'.

INSERT TABLE 1 HERE

Arithmetic task

Stimuli. Forty-eight trials were presented to each participant. Each trial consisted of three consecutive items (i.e., three two-digit multiplication problems), followed by a letter-judgment task involving a series of four letters. As in previous experiments of ours, this letter-judgment task was used as a filler to prevent interference between the last item of a trial and the first item of the next trial (see Hinault, Dufau, & Lemaire, 2014; Lemaire & Hinault, 2014; Lemaire & Lecacheur, 2010; Lemaire & Leclère, 2014). Half of the four letter series included either only consonants or only vowels, and half included both types of letters. Arithmetic problems were either homogeneous problems (i.e., precursor items) or heterogeneous problems (i.e., target items). Homogeneous problems were problems with the unit digits of both operands smaller than 5 (e.g., 32 x 64) or larger than 5 (e.g., 37 x 69). Half the homogeneous problems were considered easy problems because their unit digits of both operands were smaller than 5 (e.g., 41 x 64), and half the homogeneous problems were considered hard problems because their unit digits of both operands were larger than 5 (e.g., 39 x 47). Heterogeneous problems were considered as problems of intermediate difficulty since they had one operand with its unit digit smaller than 5 and the other with its unit digit larger than 5 (e.g., 43 x 69).

These problems were chosen because previous work (e.g., Taillan, Ardiale, & Lemaire, 2015) showed that easy and hard homogeneous problems generated better and worse performance respectively, and that heterogeneous problems generated intermediate performance between easy and hard homogeneous problems. Following previous findings in arithmetic (see Campbell, 2005, for an overview), we selected problems with the following constraints: (a) no operands had a 0 unit digit (e.g., 20 x 63) or a 5 unit digit (e.g., 25 x 63); (b) no digits were repeated within operands (e.g., 22 x 63); (c) no reverse orders of operands were used (e.g., 24 x 63 and 63 x 24); (d) the first operand was larger than the second operand in half the problems, and vice versa; (e) no operand had its closest decade equal to 0, 10, or 100; and (f) rounded operands were never the same across two rounding problems in a given trial (e.g., if one problem in a trial was 32 x 64, the next problem could not be 31 x 62).

Procedure. The experimental stimuli were displayed horizontally in 100-point Courier New font (black color) in the center of a 15.6-inch computer screen controlled by a DELL Latitude D420 computer. The software (E-Prime) controlled stimulus display and latency collection. Participants were told that they were going to do computational estimation. The computational estimation task was explained as giving an approximate answer to an arithmetic problem that is as close as possible to the correct answer without actually calculating it. Because previous works showed that participants used several strategies to solve arithmetic problems, to control for age differences in strategy repertoire and strategy distribution, we restricted the strategy repertoire to only two strategies. These two strategies are known to be used spontaneously by young and older adults in comparable proportions. Thus, participants had to estimate the product of each (homogeneous or heterogeneous) problem displayed on the screen, using either the rounding-down strategy (e.g., rounding both operands down to the nearest decades, for instance doing 60 x 30 to estimate 63 x 38) or the rounding-up strategy (e.g., rounding both operands up to the nearest decades, for instance doing 70 x 40 to estimate 63 x 38). None of these strategies were explicitly cued. However problems were selected so that their characteristics (i.e., size of unit digits) led participants to use the best rounding strategy on each problem. Previous works of ours (e.g., Lemaire et al., 2004) showed that participants used rounding down on almost all small-unit digit problems (e.g., 41 x 62) and rounding up on all large-unit digit problems (e.g., 47 x 38).

After an initial practice period including six problems (three easy and three hard homogeneous problems), all participants had no difficulties to estimate the products of multiplication problems (i.e., none of them tried to calculate the exact product). Then, participants practiced for three trials, each including three problems (two easy or hard homogeneous problems and one heterogeneous problem) and a series of four letters for them to get familiarized with the procedure and the structure of each trial. Finally, in the experimental part, participants solved 48 trials with a break after each block of 12 trials, yielding a total of 144 items.

Two conditions were presented to participants: i) an unrepeated-precursor condition and ii) a repeated-precursor condition. Both unrepeated- and repeated-precursor conditions included exactly the same individual problems. The only difference between the two conditions was in the order of problems. The unrepeated-precursor condition was composed of a precursor problems (easy or hard problem) followed by a target problem (problem of intermediate difficulty), itself followed by a post-target problem (easy or hard problem). For example, the unrepeated-precursor condition included the following problems: 48 x 67, 34 x 59, 79 x 28, with 48 x 67 as the precursor problems, 34 x 59 the target problem, and 79 x 28 the post-target problem. The repeated-precursor condition was composed of repeated-precursor problems followed by a target problem (e.g., 48 x 67, 79 x 28, 34 x 59). For the precursor problems to be exactly the same in both unrepeated- and repeated-precursor conditions, each first problem of the repeated-precursor condition was the same as the post-target problem of the corresponding unrepeated-precursor condition. Precursor and/or post-target problems were either easy (E) or hard (H) problems while target problems were always of intermediate (I) difficulty. Thus, unrepeated-precursor trials included EIE and HIH problems; and repeated-precursor trials included EEI and HHI problems. Precursor difficulty was controlled so that there was no more than a repetition of the same precursor trial difficulty. The same set of stimuli was administered to all participants in a counterbalanced order of presentation. Thus, all participants were tested in both the unrepeated- and repeated-precursor conditions. Half the participants were tested in the unrepeated-precursor condition first and in the repeated-precursor condition second. The other participants were tested in the reverse order for the two conditions.

The trial procedure is illustrated in Figure 1. Each trial began with a 500-ms blank screen before a 400-ms warning signal (“#”) displayed at the center of the screen, followed by the first problem. Then, another 500-ms blank screen, a 400-ms warning signal, and then the second problem, followed again by the 500-ms blank screen and the 400-ms warning signal, then the third problem. The timing of each response began when the problem appeared on the screen and ended when the experimenter pressed the spacebar on the computer keyboard, the latter event occurring as soon as possible after the participant started to respond verbally. To avoid experimenters’ expectations influencing the response time measurement, we used a double-blind procedure. Moreover, participants were asked to calculate out loud so that the experimenter could write down the answers given and later identify any errors of estimation. Thus, no error feedback was given to participants.

After the last multiplication problem of each trial, a blank screen followed the participant’s response for 500 ms, then, the warning signal appeared for 400 ms followed by four letters (e.g., *thlm*). Letters were presented until the participant responded, pressing the green response-key when the four letters were only consonants (e.g., *trlc*) or only vowels (e.g., *aeyo*), and the red response-key when the four letters included both consonants and vowels (e.g., *ubqi*). A blank screen was finally displayed for 1,000 ms at the end of each trial and before the next trial started (see Figure 1).

INSERT FIGURE 1 HERE

Aiming task

Stimuli. Participants performed 48 trials. Each trial consisted of three consecutive items (i.e., three consecutive areas to reach). The index of difficulty (ID, in bits) for the Fitts aiming task was scaled via the manipulation of the size of the finish area. Difficulty increases with decreasing the size of the finish area. Three area widths (W) were used: 5, 1.3, and 0.3 cm. The distance (D) between the start area and the center of the finish area was held constant (20 cm). Three different IDs were tested: ID_3 (i.e., 3 bits) and ID_7 (i.e., 7 bits) were precursor items and ID_5 (i.e., 5 bits) was used for target items. ID_3 items were considered easy precursor items because the reaching finish areas were large (5 cm), and ID_7 items were considered hard precursor items because the reaching finish areas were small (0.3 cm). There were equal proportions of easy and hard precursor items. ID_5 items were considered to be of intermediate difficulty because the reaching finish areas were of intermediate width (1.3 cm).

Procedure. Participants were seated in front of a Wacom graphic tablet (Intuos4 XL) positioned on a tabletop. The graphic tablet was connected (via a USB port) to a portable PC (Dell, Latitude D420) placed about 60 cm in front of the participant at eye level. The task consisted of performing rapid pointing movements with the right arm, by sliding a hand-held non-marking stylus (Wacom, Generation 2 tip sensor) over the surface of the tablet. Sliding movements were performed on the tablet in order to move an on-screen displayed cursor (i.e., a yellow vertical line of 1 mm) from a start area (i.e., a rectangular blue area of 2 mm) towards a finish area (i.e., a rectangular red area; Figure 2). Participants were instructed to adopt the most comfortable position in order to make left-to-right movements, parallel to the longer side of the tablet, by extending the shoulder and elbow. The trunk position was restricted by the chair-back position and the front edge of the table.

INSERT FIGURE 2 HERE

Before each trial, participants were asked to hold still the yellow cursor on the blue home area until they heard an auditory signal. Participants were instructed to keep optimal speed-accuracy trade-off while executing the movement that is “move the cursor as fast as possible from the home area to stop in the finish area”. Moreover, no error feedback was given to participants.

The mapping between the movement of the stylus on the tablet and that of the cursor on the screen was linear and of constant gain (gain = 1). The ID displacement of the cursor on the screen was displayed on the screen as an online feedback during movement execution. Participants were allowed to complete two (unrecorded) familiarization trials, each involving three different IDs. Then, participants completed the aiming task in 12 blocks of 12 trials each, for a total of 144 items, with a break between blocks.

Two conditions were presented to participants: i) an unrepeated-precursor condition and ii) a repeated-precursor condition. Both unrepeated- and repeated-precursor conditions included exactly the same IDs. The only difference between the two conditions was in the order of IDs. The unrepeated-precursor condition was composed of a precursor item (i.e., ID_3 or ID_7) followed by a target item (i.e., ID_5), itself followed by a post-target item (i.e., ID_3 or ID_7). For example, an unrepeated-precursor condition included the following IDs: ID_3 - ID_5 - ID_3, with ID_3 as the precursor item, ID_5 the target item, and ID_3 the post-target item. The repeated-precursor condition included repeated-precursor items followed by a target item (e.g., ID_3 - ID_3 - ID_5). Precursor and/or post-target items were either easy (E) or hard (H) whereas target items were always of intermediate (I) difficulty. Thus, unrepeated-precursor trials included EIE and HIH items; and repeated-precursor trials included EEI and HHI items. Precursor difficulty was controlled so that there was no more than a repetition of the same precursor trial difficulty. The same set of stimuli was administered to all participants in a counterbalanced order of presentation. Thus, all participants were tested in unrepeated- and repeated-precursor condition. Half the participants were tested in the unrepeated-precursor condition first and in the repeated-precursor condition second. The other participants were tested in the reverse order for the two conditions.

Data processing. The pen-tip raw displacement data were recorded at a sampling frequency of 250 Hz, using a customized software (ICE) developed at the laboratory (Institute of Movement Sciences, Marseille). The recorded data were filtered with a second-order dual pass (no phase-lag) Butterworth filter (cutoff frequency of 10 Hz). First, second, and third derivatives of displacement (velocity, acceleration, and jerk, respectively) were then computed in MATLAB (MathWorks, v.7.5.0 R2007b). Movement onset and offset were determined on the basis of velocity profiles using the optimal algorithm of Teasdale, Bard, Fleury, Young, and Proteau (1993). The critical velocity threshold was obtained by multiplying peak velocity by 0.05.

This procedure allowed us to calculate for each item, in each condition, the movement time (MT) corresponding to the time to reach the finish area, and the effective finish area width (We). The We was calculated from the standard deviation of movement end points (Mackenzie, 1992) using the following formula: $We = 2*1.96*SD_A$, where SD_A is the Standard Deviation of movement amplitude, and 1.96 is the boundary of a normal distribution at 95%. Then, to check whether the prescribed IDs were respected (Sleimen-Malkoun et al., 2012), we compared the distributions of movement end points (centered on mean movement amplitude and bounded by calculated We), and the prescribed ones (centered on finish area distance and bounded by finish area edges). These comparisons yielded no significant statistical differences (ts < 1). As a consequence, the prescribed ID levels were used for all participants.

Results

The first analysis aimed at checking the relative item difficulty (based on the hard minus easy item response times) in both our arithmetic and aiming tasks and whether relative item difficulty varied with aging. The second analysis aimed at testing SDEs and how they varied across age groups. Note that preliminary analyses did not reveal any order effects in the presentation of both tasks and both conditions (*F*s < 1). Unless otherwise noted, all reported effects are significant with $p < .05$.

Effects of item difficulty

Arithmetic task. ANOVAs were performed on mean correct solution times and percentage errors (i.e., an error was made when participants' response differed from that expected given the rounding strategy that was used, as when a participant rounded both operands down to estimate 42 x 53 and gave 2,100 as a response) on the first items of each trial with mixed designs, 2 (Age: young, older adults) x 2 (Repetition: unrepeated-, repeated-precursor items) x 2 (Difficulty: easier, harder items), with repeated measures on the last two factors. Participants were faster on easier items than on harder items (3706 ms vs. 4464 ms, $F(1,36) = 30.44$, $MSe = 715866.7$, $n^2p = 0.46$). Main effects of Age ($F < 3$, ns) or Repetition ($F < 1$) or interactions involving the Age factor were nonsignificant ($Fs < 1$), as young and older adults performed equally well, and as both age-groups did not differ in relative item difficulty regardless of whether precursor items were repeated or not. Finally, the Repetition x Difficulty interaction was nonsignificant (F<1), because difficulty effects were of similar magnitudes for unrepeated- and repeated-precursor items.

Participants made 10% errors on the first item of each trial. However, no main effects (F < 1) or interactions (Fs < 4, ns) were significant.

Aiming task. ANOVAs were performed on mean correct MTs and percentage errors (i.e., an error was made when participants missed the finish area) on the first item of each trial with mixed designs, 2 (Age: young, older adults) x 2 (Repetition: unrepeated-, repeated-precursor items) x 2 (Difficulty: easier, harder items), with repeated measures on the last two factors. MTs were longer in older than in young adults (629 ms vs. 313 ms, $F(1,36) = 25.37$, $MSe = 149334$, $n^2p = 0.41$). Main effect of repetition was non significant (F < 1). Participants were faster on easier items than on harder items (362 ms vs. 580 ms, $F(1,36) = 117.27$, $MSe = 15334$, $n^2p = 0.77$). The Age x Difficulty interaction was significant ($F(1,36) = 13.03$, $MSe = 15334$, $n^2p = 0.27$), showing that difficulty effects were larger in older adults (290 ms, $F(1,36) = 104.23$) than in young adults (145 ms, $F(1,36) = 26.06$). The Repetition x Difficulty interaction was also significant ($F(1,36) = 4.80$, $MSe = 3227$, $n^2p = 0.12$), showing that difficulty effects were larger for the repeated-precursor items (238 ms, $F(1,36) = 126.90$) than for the unrepeated-precursor items (197 ms, $F(1,36) = 73.27$). Finally, the Age x Repetition interaction was non significant (F < 1), revealing that the repetition of precursor items did not affect performance in both young and older adults.

Participants made 13% errors on the first item of each trial. Young adults made more errors than older adults (17% vs. 10%, $F(1,36) = 4.61$, $MSe = 335.50$, $n^2p = 0.11$). Both young and older adults made more errors on harder than on easier items (25% vs. 2%, $F(1,36) = 80.03$, $MSe = 248.29$, $n^2p = 0.69$). The Age x Difficulty interaction was significant ($F(1,36) = 8.74$, $MSe = 248.29$, $n^2p = 0.20$), showing that young adults made more errors on harder items than on easier items (32% vs. 1%, $F(1,36) = 70.83$) compared with older adults (18% vs. 3%, respectively on harder and easier items, $F(1,36) = 17.94$. No other effects were significant.

As can be seen in Table 2, participants' responses were longer on harder items than on easier items in both arithmetic and aiming tasks. Moreover, difficulty effects were of comparable magnitudes in young and older adults in the arithmetic task, whereas they were larger in older adults than in young adults in the aiming task (see Table 2). To test whether difficulty effects were independent across both the arithmetic and the aiming tasks, we contrasted z-scores for the difference between easier and harder items in each task. We found that difficulty effects in the arithmetic task were positively correlated with those in the aiming task in older adults ($r = .50$), but not in young adults ($r = -.01$).

INSERT TABLE 2 HERE

Sequential difficulty effects

Arithmetic task. We conducted a three-way ANOVA on participants' mean solution times on correctly solved target items of each trial with a mixed design, 2 (Age: young, older adults) x 2 (Repetition: unrepeated-, repeated-precursor items) x 2 (Prior Difficulty: easier, harder items), with repeated measures on the last two factors. Main effects of Age ($F < 1$) or Repetition ($F < 1$) were non significant. Participants were slower on the target items after harder items (5128 ms) than after easier items (4830 ms), yielding 298 ms SDEs ($F(1,36) = 4.73$, MSe = 711505,1, $n^2p = 0.12$). The Repetition x Prior Difficulty interaction was significant ($F(1,36) = 4.62$, MSe = 319124.5, $n^2p = 0.11$), revealing significant SDEs with repeated-precursor items (+494 ms, $F(1,36) = 8.73$), but non significant SDEs with unrepeated-precursor items (+100 ms, $F < 1$). Finally, none of the interactions involving the factor Age (Age x Repetition; Age x Prior

Difficulty; Age x Repetition x Prior Difficulty) were significant (*F*s < 1), showing comparable performance in young and older adults both overall and whichever the repetition of precursor item or its difficulty.

Corresponding ANOVA on errors revealed that participants erred on 11% of target items. This percentage was similar in young and older adults (*F* < 1) and regardless of repetition of the precursor item, as indicated by the nonsignificant Age x Repetition interaction (*F* = 1.06, ns). Both young and older adults made more errors with repeated-precursor items than with unrepeated-precursor items (13% vs. 9%, *F*(1,33) = 4.33, *MS*e = 122.25, n^2p = 0.12). They erred more often after harder than after easier items (13% vs. 10%, *F*(1,33) = 5.33, *MS*e = 62.95, n^2p = 0.14). The Age x Prior Difficulty interaction was significant (*F*(1,33) = 7.83, *MS*e = 62.95, n^2p = 0.19), showing that older adults made more errors after harder than after easier items (15% vs. 8%, *F*(1,33) = 12.01), whereas percentages of errors were similar after harder and after easier items in young adults (11% vs. 11%, *F* < 1). The Repetition x Prior Difficulty interaction was also significant (*F*(1,33) = 6.57, *MS*e = 57.17, n^2p = 0.17). Percentages of errors were larger after harder than after easier items with unrepeated-precursor items (*F*(1,33) = 10.65), and were similar after easier and after harder items with repeated-precursor items (*F* < 1). Finally, the Age x Repetition x Prior Difficulty came out significant (*F*(1,33) = 5.71, *MS*e = 57.17, n^2p = 0.15), showing that older adults erred more after harder than after easier items with unrepeated-precursor items (15% vs. 2%, *F*(1,33) = 20.98), but equally often on items following easier versus harder items with repeated-precursor items (14% vs. 15%, *F*<1). Percentages of errors did not differ after easier and after harder items regardless of whether the precursor items were repeated (*F*s < 1).

Aiming task. We conducted a three-way ANOVA on participants' MTs on correctly reached target items of each trial with a mixed design, 2 (Age: young, older adults) x 2 (Repetition:

unrepeated-, repeated-precursor items) x 2 (Prior Difficulty: easier, harder items), with repeated measures on the last two factors. MTs on the target items were longer in older than in young adults (615 ms vs. 323 ms, *F*(1,36) = 24.79, *MS*e = 130774, n^2p = 0.41). Neither the main effect of Repetition nor its interaction with Age were significant (*F*s < 1), revealing comparable performance for unrepeated- and repeated-precursor items in both age groups. Participants were slower on the target items after harder items (484 ms) than after easier items (453 ms), yielding 31 ms SDEs (*F*(1,36) = 5.02, *MS*e = 6946, n^2p = 0.12). The Repetition x Prior Difficulty interaction was significant (*F*(1,36) = 4.84, *MS*e = 2120, n^2p = 0.12), revealing significant SDEs for repeated-precursor items (+46 ms, *F*(1,36) = 7.07), but non-significant SDEs for unrepeated-precursor items (+14 ms, *F* = 1.14, ns). The Age x Prior Difficulty interaction was significant (*F*(1,36) = 4.31, *MS*e = 6946, n^2p = 0.12), as SDEs were significant in older adults (+59 ms, *F*(1,36) = 9.31) but not in young adults (+3 ms, *F* < 1). Finally, although the Age x Repetition x Prior Difficulty interaction was not significant, we ran breakdown analyses to analyze SDEs in each age group as a function of whether the precursor items were repeated or not. We found that SDEs in older adults occurred only when the precursor items were repeated (*F*(1,36) = 11.74). SDEs were non-significant in older adults when tested with unrepeated-precursor items (*F* = 2.95, ns) and in young adults tested with both repeated- and unrepeated-precursor items (Fs < 1).

Participants erred on 7% of target items. Young adults made more errors than older adults (9% vs. 5%, *F*(1,36) = 4.67, *MS*e = 150.91, n^2p = 0.11). No other effects were significant.

As can be seen in Table 3, we found SDEs in both arithmetic and aiming tasks only in the repeated-precursor condition. Moreover these effects were similar in young and older adults in the arithmetic task, whereas they were found only in older adults in the aiming task (see Table 3).

INSERT TABLE 3 HERE

Discussion

In the present study, we investigated SDEs in an arithmetic task and in a Fitts aiming task for the same young and older adults. Above and beyond replicating previous findings regarding SDEs, new findings were observed in the present experiment.

As a prerequisite, our results replicated SDEs in both cognitive and sensorimotor tasks. Indeed, we found that the difficulty of the precursor item influenced participants' performance on current items. Specifically, participants were slower on current items after solving harder problems or after reaching smaller areas relative to easier problems or larger areas. Moreover, the standardized effect-sizes were equivalent for the main effects of prior difficulty on the latencies in both the arithmetic and aiming tasks (i.e., .12) and were similar for its interaction with repetition. Effect-sizes of the present SDEs were weaker than those reported by Schneider and Anderson with .30 and .24 for task switches and .36 and .15 for problem-based switches (Schneider & Anderson, 2010, Experiments 1 and 2) and again, of .40 for a rounding-up/down strategy switch in another arithmetic study (Uittenhove & Lemaire, 2012, Experiment 1) and finally .52 for the item-based difficulty switch in Poletti et al' s (2016) study.

However, results also showed that SDEs occurred in both tasks only when participants had to perform the repeated-precursor item condition. This result is surprising because in previous cognitive and sensorimotor studies (e.g., Poletti et al., 2016; Schneider & Anderson, 2010), SDEs were observed with unrepeated-precursor items. A plausible explanation is that, in the present study, the domain-specific resources that were used on the preceding items were not sufficiently taxed to produce SDEs with unrepeated-precursor items. Also, participants had to switch between three strategies in previous studies, and between two strategies from one trial to the next in the present arithmetic task. Indeed, performance on the target arithmetic problems estimated with a mixed-rounding strategy (e.g., rounding the first operand up and the second down) were compared with performance when the previous problems were estimated with either a rounding-down strategy or a rounding-up strategy in the previous studies. Here, we did not test mixed-rounding strategy.

In the repeated-precursor condition, presumably, fewer resources were available on current items. As a consequence, SDEs were observed in both arithmetic and aiming tasks. This hypothesis is supported by the fact that for the precursor items themselves, there were very strong main effects of difficulty (i.e., .46 for arithmetic, and .77 for aiming) and a Repetition x Difficulty interaction, at least for the aiming task (i.e., 0.12). Indeed, this interaction could implicate prospective processes (expectancy/preparation) in realizing an effect of repetition as an artefact of the administration of repeated- and unrepeated-difficulty trials in pure blocks.

It is also consistent with findings from an arithmetic study carried out with a similar design, which showed that participants repeated more often the same strategy on the current problems after repeated- than after unrepeated-precursor strategies (Lemaire & Leclère, 2014). Moreover, it seems relevant to consider that, at least for the arithmetic task, this study used a longer response-stimulus interval (RSI) within trials (i.e., 900 ms) than in previous studies (i.e., RSIs were 300 ms in Schneider & Anderson, 2010, and 500 ms in Uittenhove & Lemaire, 2012). It is possible that because of unrepeated-precursor items and increased RSI, SDEs did not occur in the present study. This would be consistent with the resource depletion hypothesis, according to which with sufficient time, processing resources within the cognitive system can replenish.

Observing SDEs in both domains with the same group of participants suggests that SDEs rely on a general mechanism of resource depletion. Participants have used up a large amount of their available resources to perform repeated difficult precursor items, leading to a depletion of the available resources on the current items, thus hindering performance. Moreover, the present results also suggest domain-specific mechanisms because SDEs found in the arithmetic task did not correlate with SDEs found in the aiming task ($r < .03$, $p > .05$). Correlation analyses of item difficulty effects across tasks were also computed given that it preempts between-task dissociation among young adults. Results showed that item difficulty effects did not correlate between tasks (rs < .37, $p > .05$).

Most interestingly, the present data revealed SDEs of comparable magnitudes in young and older adults for the arithmetic task and SDEs in older adults only for the aiming task. Note that older adults made more errors on target items after unrepeated harder precursor problems than after unrepeated easier precursor problems, resulting in SDEs on error rates. The lack of differences between young and older adults' SDEs in the arithmetic task could be due to compensation mechanisms in older adults. Indeed, in this task, performance on the first problems of each condition in older adults did not differ from those of young adults, suggesting that good arithmetic skills could have helped them compensate for SDEs. Moreover, older adults obtained higher arithmetic fluency scores than younger adults (see Table 1). However, arithmetic scores did not correlate with SDEs in young or older adults ($rs < -.33$, $p > .05$; see Uittenhove & Lemaire, 2013, for similar results).

In the aiming task, in contrast to young adults, older adults were slower in reaching the current areas after reaching repeated smaller areas than after reaching repeated larger areas. This is a different result from our previous study where no age-related differences in SDEs were found. A possible explanation is that older adults allocated more attention to more demanding central processing of sensory information for online monitoring movements than young adults, especially when they had to reach repeated smaller areas. Such increased cognitive control of movement presumably relies on the recruitment of executive functions that support planning, control, and execution of complex tasks (see Yogev-Seligmann, Hausdorff, & Giladi, 2008; Woollacott & Shumway-Cook, 2002, for supporting evidence in gait and posture studies). It is possible that the well-known age-related decrease in executive control processes (see Diamond, 2013), combined with greater processing demands (i.e., reaching two successive hard areas) during online monitoring of movements led to increased age-related differences in SDEs during the aiming task.

Another possibility lies in the nature of strategies used by young and older adults. As previous studies in a number of domains found, young and older adults often differ in the strategies they use to accomplish tasks (see Lemaire, 2016, for an overview). Here, it is possible that young and older adults used different movement strategies as supported by our previous works (see Poletti, Sleimen-Malkoun, Temprado, & Lemaire, 2015; Poletti et al., 2015, 2016). Specifically, depending on the type of sub-movements observed in the kinematic profiles (i.e., no submovements, Type 1, 2, and 3 submovements), four specific strategies were distinguished (i.e., the one-shot, overshoot, undershoot, and progressive-deceleration strategies, respectively) in these previous studies. Although these strategies were used by both young and older adults, young adults used the easier one-shot strategy more often whereas older adults used the harder undershoot strategy more often when they were told to perform rapid-aiming movements. Thus, in the present study, if older adults have used harder strategies more often on repeated-precursor items compared to young adults, they could have fewer available resources to reach the current areas, explaining these age-related differences in SDEs. We did not test this hypothesis here since, in Fitts task, the control of the strategies (e.g., via instructions) that participants execute was impossible.

Conclusion and perspectives

These findings further improve our understanding of the nature of the processes underlying cognitive and sensorimotor performance in young and older adults. For the first time, SDEs were investigated in the same participants performing both cognitive and sensorimotor tasks. Whatever the domain, we found that young and older adults’ performance on current items were influenced by the difficulty of the precursor items. These results suggest that aging influences general mechanisms governing both cognitive and motor performance. Moreover, they showed domain-specific alterations with aging, such as greater SDEs during sensorimotor Fitts’ aiming task. More research will be needed to fully determine the underlying mechanisms and the effect of aging (e.g., by examining the possibility those age-related differences found here stem from strategy differences).

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Table 1.

Participants' characteristics

Characteristics	*Younger adults*	*Older adults*	*Means*	*F*
N (Females)	19 (8)	19 (15)	--	--
Mean age (*SD*)	24.9 (3.5)	73.7 (5.5)	49.3 (25.1)	--
Age range	19-32	65-83	--	--
Years of education (*SD*)	16.7 (2.7)	13.1 (1.7)	14.9 (2.9)	24.61*
MHVS[1] (*SD*)	24.8 (4.4)	26.1 (3.4)	25.5 (3.9)	2.60
Arithmetic fluency (*SD*)	49.4 (14.7)	73.8 (21.0)	61.6 (21.7)	17.26*
MMSE[2] (*SD*)	--	29.0 (0.9)	--	--

Note. [1] Mill-Hill Vocabulary Scale, [2] Mini-Mental State Examination. *$p < .001$.

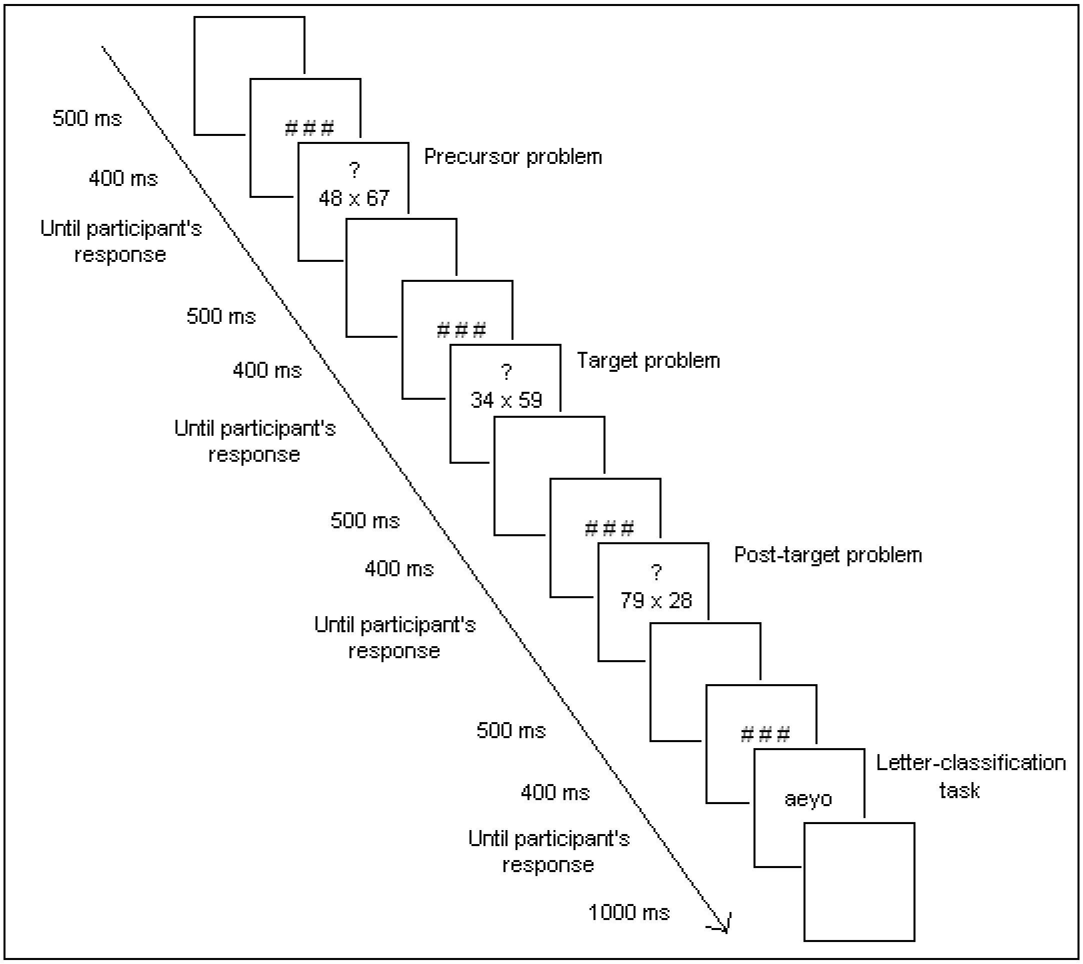

Figure 1. Example of trial procedure for the arithmetic task. Trial is presented with unrepeated hard precursor problem.

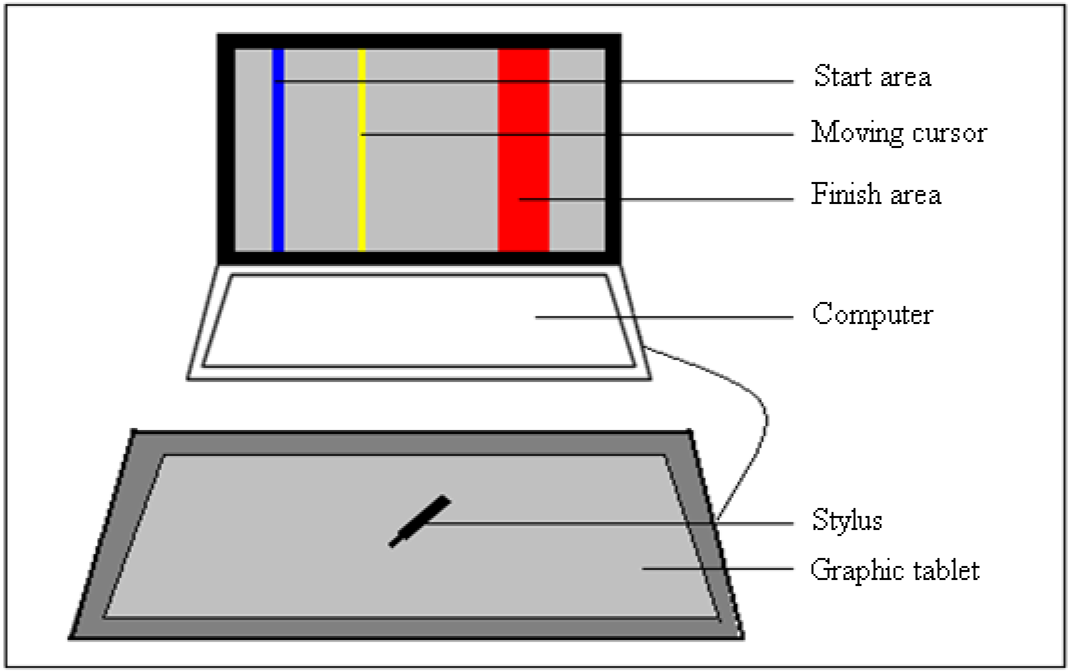

Figure 2. Front view of the experimental setup for the aiming task.

Table 2.

Effects of item difficulty on solution latencies (ms) and percentages of errors as a function of task (arithmetic or aiming), age (young or older adults) and repetition (unrepeated- or repeated-precursor items).

Performance	Solution latencies			Percentage of errors		
	Young	Older	Means	Young	Older	Means
			Arithmetic task			
Unrepeated-precursor items	793	935	864	4	4	4
Repeated-precursor items	499	802	651	1	-2	-1
Means	646	869	757	3	1	2
			Aiming task			
Unrepeated-precursor items	141	254	197***	30	15	22
Repeated-precursor items	149	326	238***	31	16	23
Means	145***	290***	218	30***	15***	23

Note. *p < .05; ** p < .01; *** p < .001

Table 3.

Sequential difficulty effects in solution latencies (ms) and percentages of errors as a function of task (arithmetic or aiming), age (young or older adults) and repetition (unrepeated- or repeated-precursor items).

Performance	Unrepeated-precursor items			Repeated-precursor items		
	Young	Older	Means	Young	Older	Means
			<u>Arithmetic task</u>			
Solution latencies	111	90	100	438	550	494*
Percentage of errors	0	13***	6	-1	1	0
			<u>Aiming task</u>			
Solution latencies	-4	32	14	8	85**	47
Percentage of errors	0	1	1	4	-1	1

Note. *$p < .05$; ** $p < .01$; *** $p < .001$

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