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ORIGINAL ARTICLE

The cost of serially chaining two cognitive operations

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Abstract As Turing (1936, *Proceedings of the London Mathematical Society*) noted, a fundamental process in human cognition is to effect chained sequential operations in which the second operation requires an input from the preceding one. Although a great deal is known about the costs associated with 'independent' (unrelated) operations, e.g., from the classic psychological refractory period paradigm, far less is known about those operations to which Turing referred. We present the results of two behavioural experiments, where participants were required to perform two speeded sequential tasks that were either chained or independent. Both experiments reveal the reaction time cost of chaining, over and above classical dual-task serial costs. Moreover, the chaining operation significantly altered the distribution of reaction times relative to the Independent condition in terms of an increased mean and variance. These results are discussed in terms of the cognitive architecture underlying the serial chaining of cognitive operations.

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Introduction

During the past few decades, cognitive psychologists have gained considerable insight into the organization behind a *single* cognitive operation including how an elementary decision is reached by the accumulation of sensory evidence. Yet to date, we still have surprisingly little knowledge of the cognitive mechanisms by which *multiple* elementary operations are sequentially assembled into mental 'routines', especially when a cognitive operation partially or completely depends on the input from a previous cognitive operation—a situation called 'chaining'. Such chaining operations are vital for human decision making in everyday life; a behavioural understanding of which constitutes the motivation for the present report.

Temporal proximity between two cognitive operations, even if they are not chained, reveals a resource conflict. Indeed, several behavioural observations such as the phenomena of the psychological refractory period (PRP; cf. Pashler, 1984; Sigman & Dehaene, 2005, 2006) and the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992) demonstrate our inability to process multiple independent stimuli when presented closely in time. Researchers have offered various accounts of the above-mentioned resource conflict. In the case of PRP, a structural central bottleneck (Pashler, 1984, 1994), a central capacity sharing mechanism (Tombu & Jolicoeur, 2003), and an adaptive executive control mechanism (Meyer & Kieras, 1997a, b), have each been proposed to account for the hallmark effect of

PRP, i.e., RT to the second of two independent tasks (both require speeded responses) increases rapidly with the decrease of SOA between them. Turning to the AB, the interference model (Shapiro, Raymond, & Arnell, 1994), the two-stage model (Chun & Potter, 1995), and the goal-directed control model (Kawahara, 2003), have been proposed to explain the AB phenomenon, e.g. the impaired ability to identify the second of two independent targets (speeded responses are *not* required) presented in close succession. At the heart of all models for both the PRP and AB phenomena lies an information processing 'bottleneck' in which the processing of one task temporarily prevents the execution of crucial steps of a temporally overlapping task.

In contrast to numerous studies investigating of the cost associated with performing two independent tasks, few experiments have been conducted to examine the cost associated with tasks where performance of the second depends on the outcome of the first. A recent report by Sackur and Dehaene (2009) describes a detailed chronometric analysis of such a 'chaining' task, which required participants to add or subtract an input number to a fixed reference digit (arithmetic operation), then compare the intermediate result with another fixed reference digit (comparison operation) to determine which was greater. The two operations of this chaining task share a single external stimulus, e.g. the input number. Using this significant departure from traditional PRP approaches, these investigators revealed a partially serial mechanism with cross-talk between the two successive tasks, i.e., the comparison operation was able to be launched prior to completion of the arithmetic operation. Importantly, however, those authors did not compare chained versus non-chained tasks and thus could not isolate the effect of chaining from the effect due to temporal proximity. This vital gap is what the present study seeks to fill (see "General discussion" for a more complete treatment of this issue).

To accomplish our goal a novel variation of the PRP paradigm was derived, which required two successive tasks to be performed: In one, Independent condition, successful performance of the second task was unrelated to the first, as is the case in a typical PRP experiment. In the second, Chained condition, successful performance of the second task was dependent on successful performance of the first. Our goal was to characterise the performance difference between these two conditions, i.e., to isolate a chaining effect over and above the traditional PRP effect.

Previous evidence from PRP literature suggests that the information processing bottleneck to which we refer above arises from a central decision stage, which consumes cognitive resources and suffers from seriality. For example, Pashler (1984, 1994) argued that, whereas the perceptual (P) and response (M) stages of information processing can operate independently on each task, the bottleneck occurs when the central (C) stage must connect P to M stages. A recent model proposed by Sigman and Dehaene (2005, 2006) provides a promising *computational implementation* of the so-called 'central bottleneck' account. In their recent studies, the authors suggest that the central bottleneck occurs as a result of stochastic evidence accumulation, required prior to executing a decision. In this model, the decision-making stage is viewed as a noisy integrator that accumulates perceptual evidence from the sensory system via a 'random walk'. Sigman and Dehaene's model relates the 'psychological' bottleneck (Pashler, 1984) to accumulation-based decision mechanisms (Gold & Shadlen, 2001, 2002; Ratcliff, 1988; Usher & McClelland, 2001). Specifically, Sigman and Dehaene (2005, 2006) suggest that when two sequential operations are performed as part of a larger "routine", their central stages conflict and are forced to execute serially. When this occurs, response speed is determined by a tight succession of multiple stochastic accumulation stages (one for each task).

What prediction does the stochastic evidence accumulation model make for the present experiment? As with Pashler's (1984, 1994) central bottleneck model, this new model must account for the additional resources required to handle the increased complexity of the cognitive operations required to transfer information from the first to the second task in addition to dealing with the dual-task requirements. The stochastic accumulation model suggests the Chained condition will require additional resources during the 'central decision stage'; a stage already characterised above as 'noisy'. Accordingly, the extra demand arising from the chaining requirement will introduce further variability, in turn yielding slower RTs and, importantly, greater RT *variability*. Thus, according to the prediction of the 'stochastic evidence accumulation' model, we would expect to observe an altered distribution of reaction times, in terms of an increased mean and variance/standard deviation, of the chained condition relative to the independent condition (see "Discussion" for a full treatment of this issue).

Experiment 1

A novel PRP paradigm composed of two spatial arrow-tracking tasks was used in this experiment (see Fig. 1). Participants were instructed to respond as quickly as possible to each task using two joysticks, one in each hand. There were two conditions in this experiment. In the Chained condition, participants were instructed to remember the result of Task 1 and use it to perform Task 2. In the Independent condition, the tasks were identical but had no

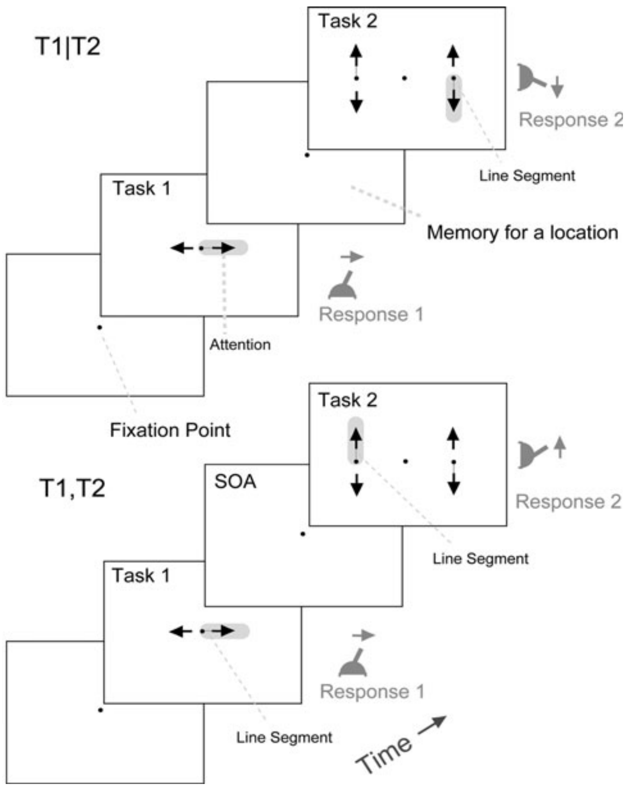

Fig. 1 Schematic representation of the tasks used to study serial processing. *Upper* in Task 1 of the Chained task (T1|T2) the participant sees two *horizontal arrows*; one of these arrows is connected by a *dim line segment* to the fixation point. The participant is required to push a joystick as soon as possible with left hand to the corresponding side of the line segment and remembers this location. For Task 2, two *vertical arrows* and one line segment appear on both sides simultaneously and the participant indicates the direction of the arrow connected to the T2 line segment of the remembered side by pushing a joystick with his/her right hand as quickly as possible. The *grey* region indicates the anticipated distribution of attention as well as the location that has to be remembered but was not present in the display. *Lower* in the independent task (T1,T2), Task 1 is identical. Task 2 is now independent from Task 1 because the participant reports about either the left or right side T2 line segment for a block of trials

dependency. Four SOAs enabled us to assess the effect of this variable.

Method

Participants

A total of 26 participants, 22 females and 4 males, aged from 18 to 35 (mean = 21; STD = 4), took part in this experiment. Half of the participants were randomly assigned to the Chained group, the other half to the Independent group. All participants were university students or employees and were paid by either course credits or cash for their participation. All participants had normal or corrected to normal vision with no history of visual or neurological disorders. This experiment was approved by the Bangor University Research Ethics Committee, and participants gave their informed consent before the experiment.

Apparatus

The participants were seated in a room which was dark except for the display. All stimuli were produced with MATLAB (Mathworks Inc.) and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and were displayed on a Dell P1130 colour monitor, driven by a NVIDIA FX 5200 Graphics adapter in a Pentium 4 host computer. The refresh rate of the monitor was 100 Hz with a display area 41° in the horizontal axis by 30.5° in the vertical axis. Participants' responses were recorded by two Competition Pro 5000 Joysticks connected to the PC via USB cables. The viewing distance between the centre of the screen and the mid point of the participant's eyes was 57 cm.

Stimuli

Two tasks were presented sequentially on each trial (see Fig. 1). In Task 1, two horizontal arrows and a single line segment connecting one of the two arrows to the fixation point were presented. Each arrow contained an equal-side triangle head (0.91° length for the side and 0.82° length for the base) and a horizontal arrow line (1.1° length). The luminance of the background and that of the arrows was 80 and 1.2 cd/m^2, respectively (measured with a Minolta CS-100 Chromameter photometer). The vertex of each arrow head was 2.91° away from the central fixation point horizontally. For a particular trial, Target 1 was to be judged "left" or "right" by virtue of on which side of the display the arrow line was connected to the central fixation point by a horizontal line segment (1° length). Participants were instructed to push the left-hand joystick horizontally (left or right) according to the location of the target as quickly as possible after the target appeared. The stimuli in the second task (Task 2) were composed of four vertically oriented arrows and two vertical line segments/targets. The size of the arrows and line segments were the same as those in Task 1, however, the orientation and presented locations were different. The vertex of each arrow head was 2.91° away from the central fixation point both horizontally and vertically. The locations of the two targets were either within top-left and bottom-right quadrants or top-right and bottom-left quadrants of the visual field. By this arrangement, one target set was always on the left and the other on the right side of the display. For Task 2, participants were instructed to use the right-hand joystick and push it vertically up or down, respectively, depending on whether the upper or lower arrow was connected to the centre point. Unlike Task 1, Task 2 contained a target on both the right and left, so participants required additional information to perform Task 2 correctly. In the Chained group (T1|T2; upper display in Fig. 1), this extra pre-cuing information was the input from the result of Task 1. For example, if the single target in Task 1 was located on the left side of the display then the left side of the display in Task 2 had to be evaluated for a response, and vice versa. In the Independent group (T1,T2; lower display in Fig. 1), this pre-cuing information (left or right target display side) was provided at the beginning of each (Independent) block.

Design

A two-factor mixed design was used in this experiment. The first factor (Chained vs. Independent) was a between-participant factor with thirteen participants in each experimental group. The second factor (SOA, stimulus onset synchrony) was a within-participant variable with four levels (100, 200, 350 and 650 ms) between Task 1 and 2. The location(s) of the target(s) in both tasks was counterbalanced across trials. Every combination of SOA was repeated sixty-four times, resulting in a total of 256 trials in each experimental session.

The experimental session was divided into 8 blocks with 32 trials in each block. For the Chained group, all eight blocks contained Chained task (T1|T2) trials. For the Independent group, four blocks contained Independent task trials (T1,T2) in which the *left* target of Task 2 was pre-defined by presenting a verbal instruction in the display at the beginning of each block. For the other four blocks, the *right* target of Task 2 was pre-defined at the beginning of each block. The order of 'left pre-defined' and 'right pre-defined' blocks in the Independent condition was counterbalanced across different participants. Unlike in the Chained condition where Tasks 1 and 2 by definition occurred in the same spatial location, in the Independent task (T1,T2) the two tasks occurred in the same location on half trials and in a different location on the other half. Thus the Independent condition had two sub-conditions, IND-stick (without a location switch) and IND-switch (with a location switch), both of which were randomly mixed within each Independent block of trials. Since the Chained condition involves no switch of spatial attention, the IND-stick trials are a more appropriate comparison to the Chained task.

Procedure

Participants were instructed to respond as quickly and as accurately as possible. Response order was also emphasized in that a Task 1 response should be always followed by a Task 2 response. A verbal instruction was presented on the display in the beginning of each block to inform participants in which block they were (Chained, Independent Left, or Independent Right). At the beginning of each trial, participants were prompted to press the 'space' key when ready. After a 750-ms blank interval, a black fixation point (radius 0.16°) was presented in the centre of the display and lasted until the presence of feedback provided at the end of each trial. Participants were instructed to perform the tasks while maintaining central fixation. Task 1 stimuli appeared at 1,000 ms after the onset of the fixation point and lasted for 100 ms, after which time only the fixation point remained. The onset of Task 2 varied according to the SOA value selected for that particular trial (for the shortest SOA values the offset of Task 1 coincided with the onset of Task 2). Task 2 stimuli remained on the display until participants made their response. Feedback was provided immediately after the occurrence of the response to Task 2 with the fixation point replaced by the feedback. The feedback took the form of two coloured dots appearing to the left and right side of the location previously occupied by the fixation dot. If the participant's response to Task 1 was correct, the left dot was green (red if it was incorrect). The same rule applied for the right dot, which represented Task 2 accuracy. The left dot was yellow if participants made no response to Task 1. The feedback dots remained on the display for 1,000 ms before initiation of the next trial.

Response grouping[1] between Tasks 1 and 2 was discouraged by presenting a yellow warning point in the location of the fixation point if Task 2 response (RT2 + SOA) was made in less than 125% of the response to Task 1 measured from Task 1 onset. Two practice blocks (with minimum 32 trials in each block) were given before the formal experiment. The first practice block used only a 1,000 ms SOA, though all other parameters remained the same as in the formal experiment, whereas the second practice block was identical to the experimental block. Participants were required to complete both practice blocks with a minimum 85% accuracy level in each before proceeding to the formal experiment. To reduce fatigue, self-controlled breaks between two continuous blocks were provided. The entire experimental session took about 50 min.

Results

Road map

Our analysis focuses primarily on the effects of the chaining operation using six dependent variables, i.e.,

[1] Response grouping is the tendency for participants to wait for the occurrence of Task 2 before initiating their response to Task 1. Procedure to discourage grouping was adapted from Van Selst and Jolicoeur (1994).

Table 1 Summary of statistical results using RT, standard deviation of RT and accuracy as dependent variables in Experiment 1

Contrast	Chained versus Independent/IND-stick						IND-stick versus IND-switch					
	RT1	STD1	Ac1	RT2	STD2	Ac2	RT1	STD1	Ac1	RT2	STD2	Ac2
Condition	*	*		*	*		*		*			*
SOA	*		*	*	*	***	*		*	*	*	*
Condition × SOA				***								

RT1 Reaction time to Task 1, *RT2* reaction time to Task 2, *Ac1* accuracy to Task 1, *Ac2* accuracy to Task 2, *STD1* standard deviation of RT1, *STD2* standard deviation of RT2

Significant main effects or interactions ($p < 0.05$) are indicated by asterisks. *** Effect only significant ($p < 0.05$) in the contrast of *Chained* versus *IND-stick* but not in *Chained* versus *Independent*

reaction time of Task 1[2] (RT1)/Task 2 (RT2), accuracy of Task 1 (Accuracy1)/Task 2 (Accuracy2) and standard deviation of RT1 (STD1)/RT2 (STD2) in six two-way ANOVAs (Condition × SOA).

Reaction time and accuracy are standard measures of assessing performance in a PRP paradigm thus constitute our primary dependent variables. For the purpose of simplifying presentation of the results, we have noted in each section that we found no speed versus accuracy trade-off. Our analysis of the standard deviation of RT was to determine if the change in mean RT was paralleled by a change in the variance. This is essential to evaluate the specific prediction of the stochastic evidence accumulation model on RT variability.

With regard to the main independent variable, i.e., Condition, follow-up ANOVAs were performed to compare *Chained* versus *Independent* (between-subject contrast), *Chained* versus *IND-stick* (between-subject), and *IND-stick* versus *IND-switch* (within-subject contrast). We note that the IND-stick condition refers to a sub-condition where, on Independent trials, Task 2 occurred in the same spatial location as Task 1. In contrast, in the IND-switch condition, Task 2 occurred on the opposite side as that on which Task 1 occurred. Thus the first of these comparisons averages over the two Independent sub-conditions (*switch and stick*) to provide an overall assessment of the effects of chaining. The second evaluates the Independent sub-condition (*IND-stick*) most comparable to the Chained condition, as there is no switch of spatial location in either. The third comparison (*IND-stick* vs. *IND-switch*) has been moved to Appendix 1 to facilitate the readability of the results. This comparison is less important as it evaluates

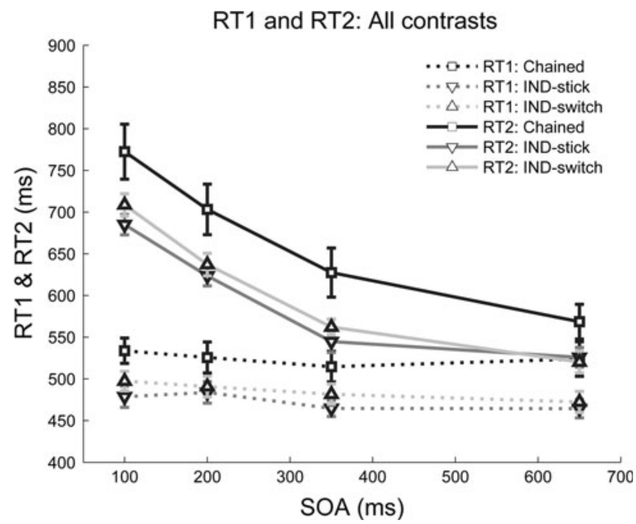

Fig. 2 Grand means of RT1 and RT2 for Chained, IND-stick and IND-switch conditions with different levels of SOAs in Experiment 1. *Vertical bars* represent standard errors. *Empty squares* for Chained condition, *downward triangles* for IND-stick condition, *upward triangles* for IND-switch condition. *Dotted curves* are for RT1 and *solid curves* for RT2

only the effect of switching spatial location and is presented in Appendix 1.

Table 1 summarizes these results showing the significant main effects and interactions. (Note that main effects and interactions not listed in this and following tables, or not mentioned in the main text, were nonsignificant and are not reported.) Figure 2 shows the grand means of RT1 and RT2 for Chained, IND-stick and IND-switch conditions at different levels of SOAs.

Effect of Condition and SOA on accuracy, RT and standard deviation

Task 1: accuracy

In terms of Task 1 accuracy, there was no significant main effect of Condition between Chained and Independent conditions ($p = 0.59$) or between Chained and IND-stick conditions ($p = 0.838$). There was, however, a significant

[2] For RT analysis, only trials with correct Task 1 and Task 2 responses and correct response order were entered into the analysis. An outlier screening procedure (Van Selst & Jolicoeur, 1994) was used to exclude outlier RTs in each cell for each participant. Less than 3.6% of trials were labelled as outliers in the RT analysis using this approach. Post hoc analyses in each ANOVA of each experiment were conducted using the Bonferroni correction for multiple comparisons.

main effect of SOA [$F(3, 72) = 13.585$, $p < 0.001$]. Task 1 accuracy at 100 ms SOA was significantly lower than that at 650 ms SOA condition (difference = −3.0%, SE = 0.9% ms, $p < 0.012$). As stated previously, there were no speed–accuracy trade-offs in this or any subsequent analysis.

Task 1: RT

The main effect of Condition was significant in the two-way ANOVA [$F(1, 24) = 4.929$, $p < 0.037$] with RT1 as dependent variable. RT1 in the Chained condition was significantly slower than RT1 in the Independent condition (difference = 47 ms, SE = 21 ms, $p < 0.037$) and RT1 in the IND-stick condition [$F(1, 24) = 6.667$, difference = 54 ms, SE = 21 ms, $p < 0.017$]. A main effect of SOA on RT1 [$F(3, 72) = 7.739$, $p < 0.001$] was also found. This main effect came from the linear decrease of RT1 from short levels of SOA (100 ms, $p < 0.002$; 200 ms, $p < 0.008$) to larger levels of SOA (350 ms). However, there was no significant quadratic trend between SOA and RT1 ($p = 0.40$).

Task 1: STD

Using the standard deviation of RT1 as the dependent variable, we found most of the effects with RT to be mirrored in the effects with STD1 in the contrast of Chained versus Independent conditions, as can be observed in Table 1. Particularly, STD1 in the Chained condition was significantly larger than STD1 in both the Independent (difference = 14 ms, SE = 6 ms, $p < 0.039$) and IND-stick conditions (difference = 19 ms, SE = 6 ms, $p < 0.006$).

Task 2: accuracy

Accuracy analyses on Task 2 revealed no main effect of Condition between Chained and Independent conditions ($p = 0.64$). However, T2 accuracy at 100 ms SOA was lower compared with other SOA levels, i.e., 200 ms (difference = −4.9%, SE = 1.2%, $p < 0.011$), 350 ms (difference = −5.3%, SE = 1.4%, $p < 0.019$) and 650 ms conditions (difference = −6.9%, SE = 1.1%, $p < 0.001$). As with Task 1, there was no speed–accuracy trade-off.

Task 2: RT

The main effect of Condition was significant [$F(1, 24) = 4.980$, $p < 0.036$] with RT2 as the dependent variable. RT2 in the Chained condition was significantly slower than both RT2 in the Independent condition (difference = 64 ms, SE = 29 ms, $p < 0.036$) and RT2 in the IND-stick condition (difference = 74 ms, SE = 30 ms, $p < 0.021$). At the same time the two-way interaction of Condition (*Chained* vs. *IND-stick*) × SOA was significant [$F(3, 72) = 2.791$, $p < 0.048$]. This interaction was derived from the difference in RT2 in the Chained condition being significantly slower than RT2 in the IND-stick condition at 3 levels of SOA, i.e., 100 ms (difference = 91 ms, SE = 36 ms, $p < 0.021$), 200 ms (difference = 81 ms, SE = 32 ms, $p < 0.019$) and 350 ms (difference = 81 ms, SE = 32 ms, $p < 0.018$), but no significant difference at 650 ms SOA ($p = 0.108$, difference = 43 ms).

The main effect of SOA [$F(1.603, 38.478) = 167.683$, Greenhouse–Geisser correction, $p < 0.001$] was also significant in the contrast of *Chained* versus *Independent*. The linear trend of SOA was significant ($p < 0.001$). Further post hoc comparisons demonstrated that RT2 of each smaller SOA level was significantly slower than RT2 of each longer SOA level. From 650 ms SOA downwards, the mean differences of RT2 were 44 ms (for 350 ms SOA, $p < 0.001$), 125 ms (for 200 ms SOA, $p < 0.001$) and 193 ms (for 100 ms SOA, $p < 0.001$), respectively. At the same time, highly significant quadratic ($p < 0.009$) and cubic ($p < 0.008$) trends between SOA and RT2 were found. Thus, there was a clear rapid increase in RT2 with a decrease in SOA, which is a hallmark pattern of PRP results.

Task 2: STD

Using the standard deviation of RT2 as the dependent variable, we found most of the effects with RT to be mirrored in the effects with STD2 in the contrast of Chained versus Independent conditions, as can be observed in Table 1. Particularly, STD2 in the Chained condition was significantly larger than STD2 in both the Independent (difference = 34 ms, SE = 14 ms, $p < 0.023$) and IND-stick conditions (difference = 47 ms, SE = 17 ms, $p = 0.011$).

Discussion

Experiment 1 revealed a PRP effect for both Chained and Independent conditions, i.e., a nonlinear increase in RT2 with the decrease of SOA between the first and second tasks. Confirming predictions of most PRP models, the interaction of Condition × SOA in Experiment 1 reveals that the cost of chaining disappears at longer SOA values, suggesting a disengagement of Task 1 from the central bottleneck. Beyond this well-established finding of classical dual-task serial costs, the design of Experiment 1 allowed us to further explore the cost of chaining, i.e., piping the results of Task 1 to Task 2. Using a variant of the PRP paradigm, we revealed two aspects of the cognitive cost associated with chaining in Experiment 1. The chaining process is revealed by RT costs in both tasks, taking the form of increased mean and variability. Such outcomes support the stochastic accumulation model, as elaborated later in the "General discussion".

Experiment 2

Experiment 1 was designed to examine the differences between processing two sequentially presented tasks when the second task is either dependent (Chained) on the first or not (Independent). To accomplish this, in the first experiment we employed a standard PRP paradigm, which typically requires a broad range of SOAs to assess the time course of the PRP effect. We employed a between-subject design because we were concerned about carry-over effects between the Chained and Independent conditions. In Experiment 2, our goal was to (1) replicate the outcome of Experiment 1, (2) explore more subtle differences between Chained and Independent conditions, and (3) examine the difference between dual- and single-target (baseline) conditions. Accordingly we chose to repeat the same experimental design from Experiment 1 but to use the same participants in both conditions, to use fewer SOAs, and to implement a single-target baseline control.

In the second experiment we made a few other minor changes as well. As we used a pre-set accuracy criterion (85%) during the two practice blocks of Experiment 1, we were concerned that participants might be over-practiced, in turn rendering accuracy a less sensitive index for measuring task difficulty. Indeed this feature, together with the between-subject design, could explain why we found no significant accuracy difference between the Chained and IND-stick conditions in Experiment 1. In Experiment 2, we omitted this pre-set accuracy criterion and used only one practice block prior to the experimental block. In Experiment 2 we used only 100 and 200 ms SOA values to gain power. Finally, in Experiment 2 we employed a single/dual-task paradigm where half of the trials contained only a single task to evaluate how Task 2 influenced performance in Task 1.

Method

Participants

Nineteen participants, 12 females and 7 males, aged 18 to 34 (mean = 20; STD = 3.5) participated in Experiment 2 and were paid by either course credit or cash.

Apparatus and stimuli

The apparatus was the same as in Experiment 1. Stimuli had the same layout as in Experiment 1, except half the trials were dual-task (containing both Task 1 and Task 2 stimuli) while the other half were single-task trials, containing only Task 1.

Design

A three-factor within-participant design was used in this experiment. The first factor, *Trial*, contained two levels: single-task (Task 1 only) and dual-task (Task 1 and 2). This factor was only used when we analysed the performance of Task 1 but not for analysing the performance of Task 2. The second factor, *Condition*, employed blocks of Chained and Independent trials, as in Experiment 1. The third factor, *SOA*, had 2 levels, i.e., 100 and 200 ms. The location(s) of the target(s) in both tasks was/were counterbalanced across trials. Every combination of trial type (single-task or dual-task), dual-task relationship (Independent or Chained) and SOA (100 or 200 ms) was repeated forty-eight times, resulting in a total of 384 trials in each experimental session.

The experimental session was divided into 8 blocks with 48 trials for each. Half the trials in each block were single-task and the other half dual-task trials with both trial types randomly mixed within a particular block. Four out of 8 blocks were 'Chained', each containing 24 dual- (T1|T2) and 24 single-task trials. The other four blocks were 'Independent', each containing 24 dual- (T1,T2) and 24 single-task trials. Two of these 4 Independent blocks were 'Left' pre-defined and the other two 'Right' pre-defined. All the other aspects of the design were the same as in Experiment 1.

Procedure

All aspects of the procedure were the same as in Experiment 1 with the following exceptions. First, for a single-task trial, since there was no second target, the fixation point remained for another 1,800 ms after Task 1 stimulus offset but terminated before the onset of the feedback. Second, the right feedback point was green by default and only became red if participants mistakenly pushed the right-hand joystick either up or down in a single-task trial before the onset of the feedback. Finally, only one practice block (containing 40 trials) was given to participants before the formal experiment. All aspects of the practice block were exactly the same as the following experimental blocks. The experimental session lasted approximately 60 min.

Table 2 Summary of statistical results using RT, standard deviation of RT and accuracy as dependent variables in Experiment 2

Contrast	Single versus dual			Chained versus IND-stick						IND-stick versus IND-switch					
	RT1	STD1	Ac1	RT1	STD1	Ac1	RT2	STD2	Ac2	RT1	STD1	Ac1	RT2	STD2	Acc2
Condition	*	*	*	*	*	*	*	*	*	*			*		
SOA[a]				*	*	*	*		*	*	*	*	*		*
Condition × SOA[a]				*	*					*					

RT1 Reaction time to Task 1, *RT2* reaction time to Task 2, *Ac1* accuracy to Task 1, *Ac2* accuracy to Task 2, *STD1* standard deviation of RT1, *STD2* standard deviation of RT2

Significant main effects or interactions ($p < 0.05$) are indicated by *asterisks*

[a] N/A for '*single* versus *dual*'

Results

Road map

As in Experiment 1 we explored the effects of chaining by six two-way ANOVAs (Condition × SOA) with the dependent variables (RT1, RT2, Task 1/Task 2 Accuracy, and the STD of RT1 and RT2). As before, separate ANOVAs were performed using the contrast *Chained* versus *IND-stick* and *IND-stick* versus *IND-switch*. A third analysis was done to explore how Task 2 affected Task 1. Table 2 shows the significant main effects and interactions for each analysis. Figure 3 shows the grand means of RT1 (thin curves) and RT2 (thick curves) for each conditions at different levels of SOA.

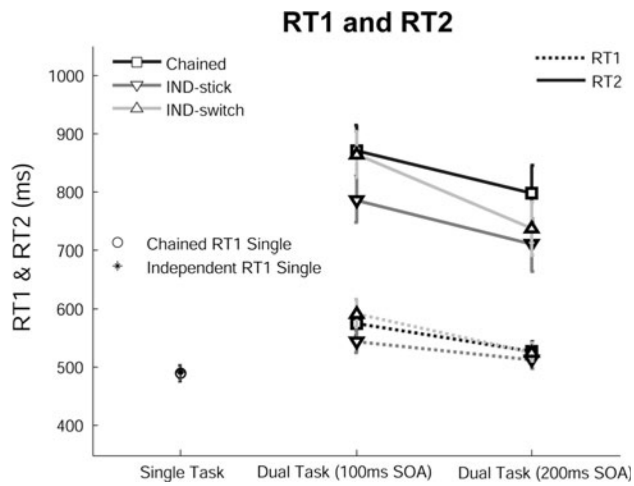

Fig. 3 Grand means of RT1 (*thin curves*) and RT2 (*thick curves*) for different conditions with different levels of SOAs in Experiment 2. *Empty squares* for Chained condition; *downward triangles* for IND-stick condition; *upward triangles* for IND-switch condition; *empty circle* for RT1 of Chained single task condition and *star* for RT1 of Independent single task condition. *Dotted curves* are for RT1 and *solid curves* for RT2. Along *x* axis, the first column is RT1 of single task trials (no T2), the second column is RT1 and RT2 of 100 ms SOA condition, the third column is RT1 and RT2 of 200 ms SOA condition. *Vertical bars* represent standard errors

Effect of Condition and SOA on accuracy, RT and standard deviation

Task 1 performance

For Task 1 accuracy, there was no significant two-way interaction. There were, however, significant main effects of Condition [$F(1, 18) = 4.597$, $p < 0.047$] and SOA [$F(1, 18) = 32.844$, $p < 0.001$]. The chained condition had lower Task1 accuracy (difference = 4%, SE = 1.7%, $p < 0.047$) relative to the IND-stick condition. The Task 1 accuracy in 200 ms SOA condition was significantly higher than that in 100 ms SOA condition (difference = 12%, SE = 2%, $p < 0.001$).

For RT1, the two-way interaction between Condition and SOA was significant [$F(1, 18) = 5.139$, $p < 0.037$]. At 100 ms SOA level RT1 of the Chained condition is significantly slower than RT1 of IND-stick condition (difference = −36 ms, SE = 7 ms, $p < 0.001$). However, this effect was only marginally significant at 200 ms SOA level (difference = −13 ms, SE = 7 ms, $p = 0.078$). Given that RT and accuracy effects are in the same direction, we can conclude that there was no speed–accuracy trade-off.

Turning to the STD of RT1, there was a significant two-way interaction of Condition and SOA [$F(1, 18) = 6.254$, $p < 0.023$]. At 100 ms SOA, the STD of RT1 in the Chained condition was significantly larger than that of the IND-stick condition (difference = 27 ms, SE = 9.4 ms, $p < 0.011$). At 200 ms SOA, this effect was not significant ($p = 0.902$).

Task 2 performance

For Task 2 accuracy, there was no significant two-way interaction. The main effects of both Chained versus IND-stick [$F(1, 18) = 12.251$, $p < 0.004$] and SOA [$F(1, 18) = 15.442$, $p < 0.002$] were significant. Task 2 accuracy in the Chained was significantly lower than that in the IND-stick condition (difference = −7%, SE = 1.9%, $p < 0.004$). The 200 ms SOA condition had higher Task 2 accuracy relative to that of 100 ms SOA (difference = −7%, SE = 1.8%, $p < 0.002$). As before there was no speed–accuracy trade-off.

For RT2 as the dependent variable, there was no significant two-way interaction. The main effect of the Chained versus IND-stick variable was significant [$F(1, 18) = 11.793$, $p < 0.004$]. The RT2 in the chained condition was significantly slower than RT2 in the IND-stick condition (difference = −78 ms, SE = 23 ms, $p < 0.004$). Further analysis by subtracting individual mean RT1 and mean RT2 of the IND-stick condition from those in the Chained condition revealed a significantly larger RT cost of chaining in RT2 relative to RT1 [$F(1, 18) = 6.703$, $p < 0.020$, RT1 cost versus RT2 cost; difference = 53 ms, SE = 21 ms, $p < 0.020$]. The main effect of SOA was also significant [$F(1, 18) = 23.261$, $p < 0.001$]. RT2 in the 200 ms SOA condition was significantly faster than RT2 in the 100 ms SOA condition (difference = −69 ms, SE = 14 ms, $p < 0.001$).

Examining the STD of RT2, there was no significant two-way interaction between Condition and SOA. The main effect of Chained versus IND-stick conditions was significant [$F(1, 18) = 8.752$, $p < 0.009$]. The STD of RT2 in the chained condition was significantly larger than the STD of RT2 in the IND-stick condition (difference = 60 ms, SE = 20 ms, $p < 0.009$). The main effect of SOA was not significant ($p = 0.831$). As with Experiment 1, the results of the analysis examining the spatial switch of attention (IND-stick vs. IND-switch conditions) has been moved to Appendix 1.

Effect of Task 2 on Task 1: dual versus single tasks

In addition to the dual-target trials required to assess the PRP effect, Experiment 2 introduced single-task trials, using an approach similar to Brisson & Jolicoeur (2007), which made it possible for us to explore how the second task might differentially affect performance of the first between the Chained and Independent conditions. Since there were two types of single-task trials (i.e., Chained and Independent), our first analysis was to evaluate any performance difference between these two types of single-task trials. Paired-samples t tests suggested that there was no significant difference in terms of mean RT1 ($p = 0.953$), accuracy of Task 1 ($p = 0.758$) and STD of RT1 ($p = 0.117$) whether this single-task trial was part of a Chained block or Independent block.

The second analysis examined whether T2 influenced T1. In the Chained blocks, RT1 of single-task trials were significantly faster than that of dual-task trials at 100 ms SOA condition (difference = 87 ms, SE = 10 ms, $p < 0.001$) and 200 ms SOA condition (difference = 36 ms, SE = 7 ms, $p < 0.001$). In the Independent blocks, the advantage of RT1 of single-task trials were 51 ms in 100 ms SOA condition (SE = 9 ms, $p < 0.001$) and 29 ms in 200 ms SOA condition (SE = 8 ms, $p < 0.004$) relative to dual IND-stick trials.

With regard to the STD of RT1, single-task trials had a significantly smaller STD in Chained blocks at the 100 ms SOA level only (difference = 56 ms, SE = 9 ms, $p < 0.001$) but not at the 200 ms SOA level ($p = 0.124$). In the Independent blocks, a smaller STD of RT1 in single-task trials was found in both 100 ms SOA condition (difference = 34 ms, SE = 7 ms, $p < 0.001$) and 200 ms SOA condition (difference = 17 ms, SE = 7 ms, $p < 0.034$) relative to dual IND-stick trials.

Discussion

Experiment 2 successfully replicated two important effects of the chaining operation observed in Experiment 1. We observed an increase in both the mean and variance of RT due to chaining. These results provide support for the stochastic accumulation model as discussed below. Given that Experiments 1 and 2 employed different experimental designs and SOA values, taken together, these two experiments suggest the robustness and generality of the effects induced by chaining. By comparing the performance for Task 1 between single- and dual-task trials, Experiment 2 also revealed that all single-task trials had similar RT1 values whether they arose from Chained or Independent blocks. However, the arrival of the second task significantly changed the distribution of RT1, i.e., revealing a larger mean and STD on dual- relative to single-task trials. At the same time, the accuracy of Task 1 was influenced by Task 2 when the SOA was at the shortest (100 ms) duration.

General discussion

The present experiments examined the behavioural consequences of chaining, where successful performance requires the output of Task 1 to be piped to Task 2, using an innovative variant of the PRP paradigm. The chaining operation was compared to a task-equivalent 'independent' operation, similar to the standard PRP paradigm, where the output of Task 1 was not required for Task 2. Both experiments, though different in design affording specific conclusions to be drawn, reveal the chaining operation to yield consistently slower and more variable[3] responding.

[3] Most mental operations are Poissonian, increasing the variance linearly with RT; there are, however a few important exceptions (cf. Wagenmakers & Brown, 2007). For example, Sigman and Dehaene (2005) showed that there are manipulations that affect mean RT without affecting the variance, e.g., changing the notation of a number from Arab digits to words in a number comparison task. It was not clear a priori whether the chaining task we inserted between T1 and T2 (which contributes to increased RT) also provided a significant contribution to the variance.

Although it is self-evident that two tasks requiring information to be transferred one to the other require more cognitive resources than the same two tasks not requiring transfer, it is nevertheless important to examine the precise nature of the costs ensued by such a demand.

The present experiments fill an important gap in our understanding of such cognitive demands when compared to a recent study by Sackur and Dehaene (2009). First, these authors did not use an 'independent' condition as used in the present experiment, thus were unable to separate the effect of chaining from temporal proximity. Second, our paradigm used two visuospatial tasks requiring separate responses to each, similar to most PRP studies. Sackur and Dehaene (2009), in contrast employed two numerical tasks that were performed on a single external stimulus, possibly triggering concurrent automatic processes. Traditional PRP tasks reveal 'cross-talk' between processing stages in a more controlled way and thus are more sensitive to differences between Chained and Independent conditions. Finally, the Sackur and Dehaene task was subject to stimulus–response (SR) mapping, potentially preventing participants from interacting directly with the underlying cognitive operations. The issue of access to underlying processes is important, as exemplified in the distinction between stimulus-based control versus plan-based control (cf. Tubau, Hommel, & López-Moliner, 2007) in the linking of actions involved in sequential learning.

We turn now to examine the implications of our results for cognitive models of dual-task processing. We do so in the context of the stochastic accumulation model (Sigman & Dehaene, 2005, 2006) for which the results of the present experiments provide support. Sigman and Dehaene proposed two cognitive operations that serve to explain the chaining effects witnessed in the present experiments. The first operation is 'task setting', i.e., planning the appropriate sequence of actions, which entails a cost to both tasks prior to execution of the first. The second arises from the execution of the chaining operation itself. This operation includes two sub-components, a buffering component to hold information from the first task, and a result-passing component to pipe previously held information to the second task. In theory, the buffering component can be initiated before the completion of Task 1, yielding RT costs to both tasks. Similar imperfect executive control has been observed in a recent study (Sackur & Dehaene, 2009) where they showed that the second operation of a chaining task can start before completion of the first. In contrast, the result-passing component exclusively affects Task 2. The timing of the initiation of the task setting and buffering components is not rigid but subject to factors such as task requirement and SOA. When task setting is initiated earlier, the chaining operation takes longer as a result of the larger effect on Task 1 due to the earlier initiation of the buffering component. It is worth noting that both sources are intrinsic components of the chaining operation, per se, in contrast to routines generated by two independent operations.

Several findings from the chaining condition of the present study support the existence of these two cognitive operations. First, 'task setting' and 'buffering' affected both tasks, whereas 'result-passing' affected only the second, accounting for the observed relatively small Task 1 but larger Task 2 cost. Second, the model's prediction that task setting and buffering components are subject to task requirements is consistent with the different outcomes observed between Experiments 1 and 2. In Experiment 1, participants knew in advance that all trials were dual-task chained or independent. Thus a rigid task-setting routine could be established prior to the start of each trial in the Chained condition. This is confirmed by the nearly constant RT1 modulation for the Chaining condition across different levels of SOA in Experiment 1. However, in Experiment 2, as participants did not know prior to Task 2 onset whether a given trial was a dual- or single-task trial, initiation of the task setting occurred rather late compared with Experiment 1; consistent with the stochastic accumulation model's prediction that the RT1 chaining cost should be larger in Experiment 1 than Experiment 2. The difference in RT between the Chained versus Independent conditions, and between Experiments 1 and 2 thus provide support for the stochastic accumulation model.

In addition to changes in RT as discussed above, the stochastic accumulation model predicts greater RT variability arising from the nature of the stochastic process by which evidence is accumulated prior to a response. Here again evidence from the present experiments support the assumptions of this model. Whereas there was a significant change in RT distribution between the Chained and Independent conditions, neither RT1 nor RT2 showed a difference in variability in either experiment when only a switch in the spatial location of attention distinguished the two conditions (IND-switch vs. IND-stick; see Appendix 1). This is consistent with the model's prediction that chaining two cognitive operations inserts an extra processing stage requiring stochastic evidence accumulation, in turn introducing variability, whereas switching the spatial location of attention does not involve such an additional central stage.

Importantly, the existence of a Task 1 *location* switch cost in both experiments supports the notion that the central processing bottleneck is not strictly serial. Rather, the results suggest that at least some resources are allocated to evaluate aspects of T2 (e.g., its spatial location in the independent condition) during the central processing stage of T1. As the classic PRP model predicts that T1 is not affected by aspects of T2, this finding is of considerable interest. Alternative proposals of central "capacity sharing" (Tombu & Jolicoeur, 2003), multiple bottlenecks (Arnell & Duncan, 2002; De Jong, 1993), or coordination by additional executive processes (Logan & Gordon, 2001; Meyer & Kieras, 1997a, b, 1999) have received considerable support in their attempts to explain the limitation of processing temporally overlapping tasks. Indeed the chaining cost observed on the first task suggests that the existence of a supervisory control system, likely linked to the functions of planning and execution, which serves to organise hierarchies of cognitive subunits into a complex goal-directed behaviour (Botvinick, 2008). Consistent with this idea, a recent study (Schumacher & Schwarb, 2009) demonstrated that implicit sequence learning of a visual–motor task is impaired by a concurrent auditory discrimination task, and that this effect arises from conflict in the central processing of the two tasks.

To conclude, both experiments consistently demonstrate that the chaining cost on the second task is relatively constant, as long as the central bottleneck is exerting an effect, i.e., at short SOAs. This implies that serial chaining can operate in parallel with PRP. This conclusion is consistent with a recent study (Miller, Ulrich, & Rolke, 2009) revealing that, in the context of the PRP paradigm, different components of multiple tasks do not always follow a strict serial mode. The authors suggest a balance between a parallel and a serial mode to optimise performance. Moreover, under certain circumstances such as overpracticed second tasks (Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008), the activation of number categories (Fischer, Miller, & Schubert, 2007; Oriet, Tombu, & Jolicoeur, 2005) and valence processing (Fischer & Schubert, 2008), the central bottleneck can even be bypassed as revealed by a reduced PRP effect. This is consistent with the idea proposed by the adaptive executive control (AEC) model (Meyer & Kieras, 1997a, b, 1999) that flexible control over secondary-task processing can be exerted and that the 'central decision stages' for two concurrent tasks may temporally overlap rather than follow a strict serial order (as suggested by an immutable structural central bottleneck). The results of the present experiments add a new and important level of understanding to dual-task interference, suggesting that some part of the chaining process, most likely the buffering component, is initiated before the completion of Task 1 and proceeds in a partially parallel way with Task 1. These results are consistent with recent literature (Sackur & Dehaene, 2009), supporting the claim that serial chaining is a relatively slow and effortful process that consumes central processing resource and requires persistent conscious control.

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Appendix 1

Spatial location switching effects: Experiment 1

With regard to Task 1 RT, a significant main effect of Condition [$F(1, 12) = 4.774$, $p < 0.05$] was found comparing the IND-stick to the IND-switch condition. RT1 of the IND-stick condition was 12 ms (SE = 5 ms) faster than RT1 of IND-switch condition. This effect was also mirrored on the accuracy of Task 1 with significantly higher accuracy of Task 1 [$F(1, 12) = 9.452$, $p < 0.011$; difference = 1.6%, SE = 0.5%] in the IND-stick condition relative to the IND-switch condition. However, this effect was not significant with regard to the standard deviation of RT1 ($p = 0.972$).

Turning to Task 2 RT, there was no significant main effect of Condition ($p = 0.191$). However, switching the spatial location of attention had an effect on Task 2 accuracy [$F(1, 12) = 9.452$, $p < 0.011$]. Accuracy of Task 2 was significantly higher (difference = 1.6%, SE = 0.5%, $p < 0.011$) for the IND-stick relative to the IND-switch condition. However, this effect of Condition difference was not significant with regard to the standard deviation of RT2 ($p = 0.313$).

Spatial location switching effects: Experiment 2

For RT1, there was a significant two-way interaction of Condition and SOA [$F(1, 18) = 10.585$, $p < 0.005$] when comparing the IND-stick to IND-switch conditions. Further post hoc comparisons revealed that this two-way interaction arose when RT1 in the 100 ms SOA IND-stick condition was significantly faster than RT1 in the IND-switch condition (difference = −44 ms, SE = 11 ms, $p < 0.002$); however, there was no significant differences at 200 ms SOA ($p = 0.199$). The main effect of Condition was significant [$F(1, 18) = 11.409$, $p < 0.004$]; RT1 of IND-stick condition was significantly faster than RT1 of IND-switch condition (difference = −27 ms, SE = 8 ms, $p < 0.004$). The main effect of SOA was also significant [$F(1, 18) = 21.517$, $p < 0.001$] with RT1 in 200 ms SOA condition significantly faster than RT1 in 100 ms SOA condition (difference = −46 ms, SE = 10 ms, $p < 0.001$). Turning to Task 1 accuracy, there was no significant two-way interaction. The only significant main effect was SOA [$F(1, 18) = 18.237$, $p < 0.001$] indicating Task 1 accuracy in 200 ms SOA condition was significantly better than that in 100 ms SOA condition (difference = 10%, SE = 2.4%, $p < 0.001$). As before, there was no evidence of a speed–accuracy trade-off.

Looking at the STD of RT1, there was no significant two-way interaction. The main effect of the IND-stick versus IND-switch comparison was not significant ($p = 0.754$). The main effect of SOA was significant [$F(1, 18) = 17.026$, $p < 0.002$]. The STD of RT1 in 200 ms SOA condition was significantly smaller than that in 100 ms SOA condition (difference = −26 ms, SE = 6 ms, $p < 0.002$).

Turning to RT2, there was no significant two-way interaction. The main effect of the IND-stick versus IND-switch comparison was significant [$F(1, 18) = 9.881$, $p < 0.007$]. RT2 in IND-stick condition was significantly faster than RT2 in the IND-switch condition (difference = −47 ms, SE = 15 ms, $p < 0.007$). The main effect of SOA was also significant [$F(1, 18) = 23.689$, $p < 0.001$). RT2 in the 200 ms SOA condition was significantly faster than RT2 in the 100 ms SOA condition (difference = −96 ms, SE = 20 ms, $p < 0.001$). For Task 2 accuracy, there was no significant two-way interaction. The only significant main effect was SOA [$F(1, 18) = 15.829$, $p < 0.002$]. Task 2 accuracy at 200 ms SOA condition was significantly higher than Task 2 accuracy in the 100 ms SOA condition (difference = 6%, SE = 1.5%, $p < 0.002$). As before, accuracy results do not provide any support for a speed–accuracy trade-off.

With regard to the STD of RT2, there was no significant two-way interaction ($p = 0.270$). The main effect of the IND-stick versus IND-switch comparison was not significant ($p = 0.093$). The main effect of SOA was not significant ($p = 0.276$).

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