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Transfer of congruency effects between Stroop and multiplication tasks: Evidence that retrieval of multiplication facts requires inhibitory control

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ABSTRACT

Inhibitory control is classically considered a domain-general process, yet recent findings suggest it may operate in context-specific ways. This has important implications for theories in other cognitive domains, such as mathematics, in which inhibitory control is proposed to play a key role. Inhibitory control has been implicated in resolving interference between competing number facts when retrieving them from memory, yet clear evidence for this is lacking. Here we report two pre-registered experiments with adults that investigated transfer of inhibitory control between interleaved Stroop and multiplication fact retrieval trials. Experiment 1 ($n = 450$) measured the congruency sequence effect, where transfer of inhibitory control between trials leads to a reduced congruency effect following an incongruent trial. Experiment 2 ($n = 370$) measured transfer of the list-wide proportion congruency effect, where the congruency effect is reduced when incongruent trials are more frequent. We found evidence of transfer of the congruency sequence effect between Stroop and multiplication. This did not differ depending on whether the Stroop task used number or animal stimuli. There was no transfer of the list-wide proportion congruency effect. These results suggest that reactive, transient domain-general inhibitory control processes are involved in retrieving multiplication facts from memory. Our findings have implications for theories of cognitive control and mathematical cognition, but caution should be taken in interpreting implications for educational interventions.

1. Introduction

Mathematics is essential for success in modern society, with higher levels of mathematics achievement associated with better employment prospects and quality of life (OECD, 2013). In particular, knowledge of mathematical facts provides a solid foundation for future learning and performance; fluent retrieval of multiplication facts (e.g. 6 × 7 = 42, 6 × 8 = 48) helps lessen the cognitive burden of calculation and allows individuals to focus on more challenging aspects of mathematics, e.g. conceptual and strategic aspects of arithmetic (Heirdsfield & Cooper, 2004). The importance of fluent access to multiplication facts is increasingly recognised, for example, the UK government has introduced a new national test to assess 8–9 year olds' knowledge of multiplication facts. Direct retrieval is the dominant, but not only, strategy for retrieval of multiplication facts by adults (LeFevre et al., 1996).

Several models of multiplication fact knowledge exist (Ashcraft, 1992; Campbell, 1995; Siegler, 1988; Verguts & Fias, 2005), which all share an assumption that multiplication facts and their answers are stored in an associative network. Operand nodes (e.g. 3,5) and products (15) are associated via links which support bidirectional activation (e.g. Rusconi et al., 2004; Rusconi et al., 2006). Due to these associations, when presented with a multiplication fact (e.g. 6 × 7) the answer to a related problem, i.e. a neighbouring problem in the same times table as one of the operands (in this case 6 × 8 = 48) might therefore interfere with retrieval of the correct answer (in this case 42). Error analyses and performance on verification tasks support this suggestion; 48 % of adults' errors (Campbell & Graham, 1985) and 70 % of children's errors (Britton-Drewry et al., 2022) on multiplication problems come from answers to closely related problems. Individuals are also slower to reject incorrect answers when they come from the times table of one of the operands within the problem (Galfano et al., 2003). Moreover, problems classified as high in proactive interference take children and adults longer to solve than problems classified as low in proactive interference (De Visscher et al., 2015; De Visscher & Noël, 2014). Here, proactive

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interference was determined by the number of previously learned problems that share at least two digits (in either the operands or the product) with the current problem.

Interference between problems implies that individuals might struggle to retrieve multiplication facts not because they lack sufficient knowledge of those facts, but because they lack the skills required to overcome interference (De Visscher & Noël, 2013, 2014). Overcoming this interference may require inhibitory control, the ability to resolve interference from competing sources of information, and/or prepotent responses, in order to suppress activation from closely related but incorrect answers and boost activation to the correct answer. In this study we use an experimental approach to test whether inhibitory control is used when recalling multiplication facts. We also investigate whether, if inhibitory control is used, it is context-specific, and whether it is proactive or reactive in nature. We discuss the importance of these three questions in turn below.

The role of inhibitory control in mathematics has been a recent focus of interest within the field of mathematical cognition (see Allan et al., 2014; Lee & Lee, 2019; Van Dooren & Inglis, 2015 for reviews). The findings from this research are largely supportive of a role of inhibitory control in mathematics (Blair & Razza, 2007; Brookman-Byrne et al., 2018; Bull & Scerif, 2001; Clark et al., 2010; Coulanges et al., 2021; Cragg et al., 2017; Espy et al., 2004; Lemaire & Lecacheur, 2011; Merkley et al., 2016; St Clair-Thompson & Gathercole, 2006; Winegar, 2013), although the evidence is mostly correlational. Measures of inhibitory control, which often involve difference or ratio scores and have low between-subject variability, are not well suited to correlational designs (Hedge et al., 2018; Rouder & Haaf, 2019; von Bastian et al., 2020). Experimental approaches are therefore better suited to detect any role that inhibitory control might play in recalling numerical facts. To date, these experimental approaches have focused on negative priming and retrieval-induced forgetting techniques.

Negative priming refers to slower and less accurate responses to information that has previously been suppressed (e.g. Tipper, 1985). Across a series of studies, Megías and Macizo (Megías et al., 2015; Megías & Macizo, 2015, 2016a, 2016b, 2016c) used a negative priming paradigm where adult or child participants verified single-digit additions. Their key finding was that when the result of the current trial (e.g. $2 + 6 = 8$) was also the result that would have occurred by multiplying the operands of the previous trial ($2 + 4 = 8$), participants were significantly slower to respond. Megías and Macizo suggested that the results of addition and multiplication problems containing the same operands are coactivated, which in turn causes interference that individuals must inhibit to retrieve the correct result: Inhibitory control mechanisms remain active on the subsequent trial which individuals then need to counteract if the correct answer is the one that was inhibited on the previous trial. However, negative priming phenomena have also been explained in terms of episodic memory retrieval of a 'do not respond' tag (e.g. Neill, 1997) or as the automatic retrieval of incidental stimulus-response associations (e.g. Rothermund et al., 2005) rather than inhibitory control. Therefore, evidence of negative priming may not be sufficient to conclude that inhibitory control is involved.

Retrieval-induced forgetting refers to the finding that repeated practice retrieving information from memory can suppress the subsequent retrieval of related but unpractised information (e.g. Anderson et al., 1994) and commonly occurs when items are stored in associative networks in memory. In the context of multiplication facts, retrieval of unpractised multiplication facts that share an operand with practised multiplication facts has been found to be slower and less accurate than unpractised facts that share no operands with practised facts (Galfano et al., 2011; Phenix & Campbell, 2004). This provides further evidence that number facts are stored in an associative network and that this generates interference between facts. The exact inhibitory mechanisms underpinning retrieval-induced forgetting are still debated however. They have been attributed to active suppression (e.g Anderson et al., 1994) or associative connections between operands and answers that are strengthened and weakened in response to top-down control signals (e.g. Camp et al., 2007; Williams & Zacks, 2001). Yet it has also been argued that the retrieval-induced forgetting phenomenon can be explained without the need for inhibitory control and instead can be attributed to a facilitative effect of context at test for both unrelated-unpractised and related-practised items compared to related-unpractised items (Jonker et al., 2013).

Taken together, findings based on negative priming and retrieval-induced forgetting provides valuable information about how arithmetic facts are represented and retrieved. However, they do not conclusively demonstrate that inhibitory control is required to resolve interference and correctly retrieve multiplication facts. More importantly, they do not clarify what the nature of any inhibitory control may be. In particular, it is unclear whether the inhibitory control resources employed are similar to those involved in other cognitive domains, or whether the inhibitory processes are specific to the multiplication network context.

In this study we aimed to provide converging evidence for the role of inhibitory control in retrieving multiplication facts using an approach from the cognitive control literature, in which inhibitory control is inferred through the congruency effect: This is the well-established finding of slower and less accurate performance on incongruent trials, where competition or conflict between two stimuli or responses needs to be resolved, compared to congruent trials where no such competition is present. The resolution or reduction of this conflict is attributed to inhibitory control mechanisms. The congruency sequence effect refers to the finding that the congruency effect is smaller following a previous incongruent trial compared to a previous congruent trial. The effect was first demonstrated by Gratton et al. (1992) who gave participants a letter flanker task (termed a noise-compatibility paradigm) and found that responses to congruent trials were faster if the previous trial was also congruent, and that responses to incongruent trials were faster and more accurate if the previous trial was also incongruent.

A large body of subsequent research has been dedicated to studying the congruency sequence effect and the cognitive processes it involves (see Braem et al., 2014; Egner, 2014 for reviews). There has been much discussion in the literature as to whether the congruency sequence effect is driven by top-down inhibitory and cognitive control processes (e.g. Botvinick et al., 2001), or lower-level stimulus-response priming processes (e.g. Hommel et al., 2004). Notably, the congruency sequence effect can still be observed when these lower-level explanations are controlled for (e.g. Duthoo et al., 2014; Kim & Cho, 2014; Weissman et al., 2014), suggesting that there are top-down control processes involved. Some theories propose an integration of the top-down and bottom-up accounts, such that control states are included in 'event files' for a task, along with task-specific stimulus and response information, which are then retrieved when cued by matching features on a future trial (e.g. Dignath et al., 2019; Egner, 2014). Alternatively, it has been suggested that the detection of conflict triggers an arousal response that strengthens currently active representations (Verguts & Notebaert, 2009). Therefore, while discovering the exact processes underpinning the conflict adaptation effect is an ongoing focus of research, there is a significant body of evidence suggesting that the conflict adaptation effect, at least in part, reflects top-down inhibitory control processes. This is therefore an appropriate paradigm to explore the role of inhibitory control in multiplication fact retrieval.

Many cognitive control researchers have used interleaving paradigms to compare whether inhibitory control processes transfer across tasks and contexts (e.g. Akçay & Hazeltine, 2011; Freitas et al., 2007; Funes et al., 2010a; Hazeltine et al., 2011; Kan et al., 2013; Kiesel et al., 2006; Wendt et al., 2006; Wühr et al., 2015; for a review see Braem et al., 2014). If the congruency sequence effect is present even when the task on the previous trial differs from the task on the current trial, it suggests that the two tasks involve similar inhibitory processes. An absence of the congruency sequence effect indicates that the inhibitory processes are context specific. Some studies using very different tasks and types of conflict have shown evidence of transfer of the congruency sequence effect between tasks, consistent with the idea of domain-general inhibitory processes (e.g. Adler et al., 2020; Freitas et al., 2007; Kan et al., 2013; Kleiman et al., 2014), although these have not always fully replicated (Aczel et al., 2021; Dudschig, 2022). In contrast, the majority of studies exploring the transfer of inhibitory control between standard cognitive control paradigms such as Stroop and Simon tasks have found that inhibitory control processes only transfer between tasks when the task sets (e.g. Akçay & Hazeltine, 2008; Kiesel et al., 2006) and type of conflict (e.g. between stimuli and/or responses; e.g. Akçay & Hazeltine, 2011; Funes et al., 2010a; Viarouge et al., 2023; Wühr et al., 2015) overlap. These studies suggest that inhibitory control processes are context-specific, supported by computational accounts of the congruency sequence effect (Blais et al., 2007; Jiang et al., 2014; Verguts & Notebaert, 2008). Braem, Abrahamse, Dutoo and Notebaert (2014) reconciled these contradictory findings by suggesting that there is a u-shaped function determined by how much the task sets interfere with each other when actively maintained in working memory. When the task sets are very similar or very different both can be maintained and transfer of inhibitory control can occur, but when the task sets are different enough to cause interference, only one can be actively maintained and transfer will not occur.

Within the field of mathematical cognition, the context-specificity of inhibitory control is an active area of interest (Borst et al., 2015; Medrano & Prather, 2023; Wilkey, 2023). The work of Borst, Houdé and colleagues has used negative priming paradigms, as described above, to indicate that both adults and children use inhibitory control to suppress misleading strategies when comparing rows of items of similar length but with different numbers of items (number conservation; Linzarini et al., 2015) or when comparing the total number of items to a subset of those items (class inclusion; Borst et al., 2013). Interestingly, the negative priming effect appears to transfer across these tasks (Borst et al., 2012), as well as from a colour-word Stroop task to a number conservation task (Linzarini et al., 2015), leading the authors to suggest that the inhibitory control mechanisms involved are more domain-general than context-specific.

More generally, researchers have explored whether training on inhibitory control tasks can improve mathematics outcomes, which can also help to understand the extent to which inhibitory control processes are context-specific. Some researchers have investigated whether training on standard inhibitory control paradigms, such as the go/no-go, stop-signal and flanker paradigms improves performance on mathematics tests (Honoré et al., 2020; Thorell et al., 2009). Transfer of these training effects would indicate that similar inhibitory control processes are applied across many domains. Others have built on theories that inhibitory control processes are context-specific and embedded within domains of knowledge (McClelland & Rogers, 2003; O'Reilly et al., 2010) and have therefore developed and tested context-specific inhibitory control training programs (Wilkinson et al., 2020). Evidence for transfer of both types of interventions to mathematics achievement is limited. Moreover, intervention studies, especially those run within a classroom context, are likely to be influenced by a large number of factors. Using an experimental approach provides a simpler test to determine whether the transfer of inhibitory control is context-specific and applied in a similar way across cognitive domains.

Another factor of interest when thinking about the mechanisms underpinning the transfer of inhibitory control, particularly with regards to interventions, is the extent to which it is proactive, and instigated in advance of when it required, potentially over a long period of time, or reactive, and instigated in the moment that it is required, potentially only for a short period of time. This question has been investigated within the inhibitory control literature by studying different types of transfer effects. The congruency sequence effect discussed above refers to a reduction in the congruency effect (in speed and/or accuracy) on a trial when the preceding trial is incongruent compared to congruent (Gratton et al., 1992). This is interpreted as reflecting a reactive, transient deployment of inhibition on a trial-by-trial basis. In contrast, the list-wide proportion congruency effect refers to the reduction in congruency effects across blocks of trials that contain a higher proportion of incongruent trials compared to blocks that contain a higher proportion of congruent trials (Logan & Zbrodoff, 1979). This is interpreted as a proactive, sustained deployment of inhibition across a whole task (Braem et al., 2019). Studies that have directly compared the transfer of these two types of inhibitory process suggest that proactive, sustained proportion congruency effects are more likely to transfer across different tasks than reactive, transient, congruency sequence effects (Funes et al., 2010b; Torres-Quesada et al., 2013; Wühr et al., 2015). This question has not yet been explored within the domain of mathematical cognition.

1.1. The present research

Our research used an experimental approach to investigate the role of inhibitory control in multiplication fact retrieval by interleaving trials of a Stroop paradigm with a multiplication task. First, we aimed to investigate whether inhibitory control transfers between an established inhibitory control paradigm (Stroop task) and a multiplication fact retrieval task (Research Question 1). This would provide experimental evidence that inhibitory control is recruited when performing mathematics. More specifically, it would demonstrate that resolving interference between neighbouring multiplication facts requires inhibitory control. Second, we tested whether the transfer of inhibitory control is dependent on the stimuli that are used (Research Question 2). Transfer between a non-numerical Stroop task and the multiplication fact retrieval task would be consistent with the notion that the inhibitory control required for resolving interference between neighbouring multiplication facts is similar to that applied in other cognitive domains. Alternatively, if transfer only occurs between a numerical Stroop task and the multiplication fact retrieval task, this would indicate that the inhibitory control required for resolving interference between neighbouring multiplication facts is stimulus-specific and embedded within the numerical domain. Finally, we explored the extent to which inhibitory control mechanisms in multiplication fact retrieval are reactive and transient (i.e., congruency sequence effect) and/or proactive and sustained (i.e., list-wide proportion congruency effect; Research Question 3). To answer these questions we conducted two pre-registered studies that focused on the congruency sequence effect and the list-wide proportion congruency effect respectively. Both experiments were approved by [removed for blind review] Ethics committee (#F1271).

2. Experiment 1

2.1. Method

2.1.1. Transparency and openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study, and we follow the Journal Article Reporting Standards (JARS, Kazak, 2018). All data and analysis code are available at https://doi.org/10.17605/OSF.IO/ZM4AT. Data were analyzed using R(R Core Team, 2020) and the package ggplot,(Wickham, 2016) as well as JASP (JASP Team, 2021). The design, hypotheses and analyses were preregistered (Experiment 1: https://aspredicted.org/7zdd-r98t.pdf; Experiment 2: https://aspredicted.org/w5bp-tt87.pdf).

2.1.2. Participants

450 adults aged 18–29 years (mean = 24.34, SD = 3.60, 299 female, 149 male, 2 prefer not to say) participated. This sample size was determined from an a priori power analysis using the Superpower package in R (Lakens & Caldwell, 2021) with effect size estimates from a preparatory study investigating the impact of trial order on the conflict

adaptation effect ($N = 160$). A sample size of 450 provides 98.65 % power to detect a 2 × 2 × 2 interaction in accuracy ($\eta_p^2 = 0.02$) and 89.45 % power to detect a 2 × 2 x 2 interaction in RT ($\eta_p^2 = 0.014$), at an alpha level of 0.025. We set alpha at 0.025 to control for multiple comparisons so that we could interpret effects either in terms of accuracy or RT. Participants were recruited through Prolific, and we used Prolific's filters such that all participants reported being aged 18–30 years, spending most of their time in the UK before the age of 18, had English as their first language, and had not taken part in any of our previous studies.

The experiment was run online. Participants were presented with two attention checks in the instruction screens during the practice phase of the experiment. In accord with our pre-registration, participants who failed the first attention check did not continue with the experiment. Participants who failed subsequent attention checks were reminded to pay attention but were not excluded. In addition to the main experimental task participants completed a non-verbal reasoning screener and a multiplication fact screener in order to characterise the sample, ensure that participants met basic requirements in terms of general cognitive skills and multiplication fact fluency, and were matched between groups and experiments. Those who performed below our pre-registered criteria (< 11 on the non-verbal reasoning screener and < 28 on the multiplication fact screener, based on pilot work) were excluded from the data analysis and replaced (non-verbal screener, $N = 6$; multiplication fact screener, $N = 20$; both, $N = 1$).

2.1.3. Materials

The main experimental task consisted of trials of a Stroop task and a multiplication task, interleaved in a fixed alternating order (Fig. 1). There were two Stroop task conditions, a number Stroop and an animal Stroop. Participants were randomly allocated to complete one of these two conditions based on their participant ID. Participants also completed a non-verbal reasoning screener and multiplication fact screener. All tasks were programmed in PsychoPy (https://psychopy.org; Peirce et al., 2019) and run using Pavlovia (https://pavlovia.org).

2.1.3.1. Number Stroop task. Images of eight numbers were created, four that were designated high (6, 7, 8 and 9) and four that were designated low (1, 2, 3 and 4). Each high number was presented with each low number, creating 16 number pairs. The size ratio of the pairs of stimuli was 2:1, where the larger stimulus was double the width and height of the smaller stimulus. Pairs could either be congruent (where the physical size of the low number was half that of the high number) or incongruent (where the physical size of the low number was twice that of the high number), resulting in 32 unique number pairs. The ratio of congruent and incongruent trials was 50:50. For each number pair, the location of the correct response occurred an equal number of times on the left and right in each format (congruent, incongruent) resulting in 64 unique trials. On each trial, a pair of numbers was presented on opposite sides of the screen and participants were asked to press a key (z or m) to indicate the number that was higher numerically (e.g. 7 or 2). For all tasks, the z key corresponded to the stimulus presented on the left of the screen and the m key corresponded to the stimulus presented on the right of the screen.

2.1.3.2. Animal Stroop task. Images of eight animals were created, four that were large in real-life (an elephant, a giraffe, a lion, a shark) and four that were small in real-life (a ladybird, a snail, a frog, a mouse). Each small animal was presented with each large animal, creating 16 animal pairs. The size ratio of the pairs of stimuli was 2:1, where the larger stimulus was double the width and height of the smaller stimulus Pairs could either be congruent (where the physical size of the small animal was half that of the large animal) or incongruent (where the physical size of the small animal was twice that of the large animal), resulting in 32 unique animal pairs. The ratio of congruent and incongruent trials was 50:50. For each animal pair, the location of the correct response occurred an equal number of times on the left and right in each format (congruent, incongruent) resulting in 64 unique trials. On each trial a pair of animals was presented on opposite sides of the screen, and participants were asked to press a key (z or m) to indicate the animal that was larger in real life (e.g. an elephant or a ladybird).

2.1.3.3. Multiplication task. Sixteen non-tie multiplication problems from the 3, 4, 6, 7 and 8 multiplication tables with double digit answers were selected based on a range of criteria (see Supplementary Material for more details). For each problem, four related foil answers and four unrelated foil answers were created, resulting in 128 multiplication problems and response pairs (16 problems with 8 sets of response pairs). Related foils were drawn from the times table of one of the operands in the presented problem (e.g. 20 was a related foil for 6 × 4 =). Unrelated foils were plausible solutions of similar parity and numerical size to the correct answer, but were not drawn from the times table of either operand in the presented problem (e.g. 22 was an unrelated foil for 6 × 4 =). We refer to the related foils as interfering (i.e. incongruent) trials and the unrelated foils as non-interfering (i.e. congruent) multiplication trials respectively. On each trial a multiplication fact (e.g. 6 × 7) was presented, along with two answers presented below the multiplication fact on opposite sides of the screen. (e.g. 42 and 48). Participants were asked to press a key (z or m) to indicate the correct answer.

For each multiplication problem, the location of the correct response occurred an equal number of times on the left and right in each format (interfering, non-interfering) resulting in 256 unique trials.[1]

2.1.3.4. Non-verbal reasoning screener. We used the Matrix reasoning item bank (MaRs-IB) developed by Chierchia et al. (2019) to measure non-verbal reasoning skills. Full details are provided in the Supplementary Material. In brief, participants were presented with 3 × 3 matrices containing eight abstract images and one empty cell in the bottom right-hand corner. Their task was to find the image that was missing from four possible alternatives. They were given 8 min to complete as many matrices as possible.

2.1.3.5. Multiplication fact screener. Participants were asked to solve 48 single-digit multiplication problems from the 2 × 2 through to the 9 × 9 times tables except those used in the interleaved multiplication task. They responded by typing their answer and then pressing the return key. Full details can be found in the Supplementary Material.

2.1.4. Procedure

The multiplication trials were intermixed with the number or animal Stroop trials to create eight blocks of 64 trials. We constrained the order of the trials so that there were no more than six consecutive congruent (C) trials or six consecutive incongruent (I) trials in a row and so that there were an equal number of the four transition types (CC, CI, IC, II) within each block. Each animal stimulus was assigned a respective number stimulus such that after the Stroop trials were intermixed with the multiplication trials, the order of animal and number stimuli and the order of the multiplication trials were the same in both Stroop conditions.

In both conditions of the main experimental task (number Stroop, animal Stroop), each trial began with a blank screen (1000 ms), followed by a fixation (500 ms). Stimuli were presented between 400 and 600 ms after the fixation (creating interstimulus interval that varied between 1900 and 2100 ms). The stimuli were presented for up to 1000 ms followed by a '?' if no response had been received by this time. The trial

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[1] Due to experimenter error, half of the response locations were not reversed, resulting in some problems with the correct answer being presented in the same location in blocks 5–8 as they were in blocks 1–4.

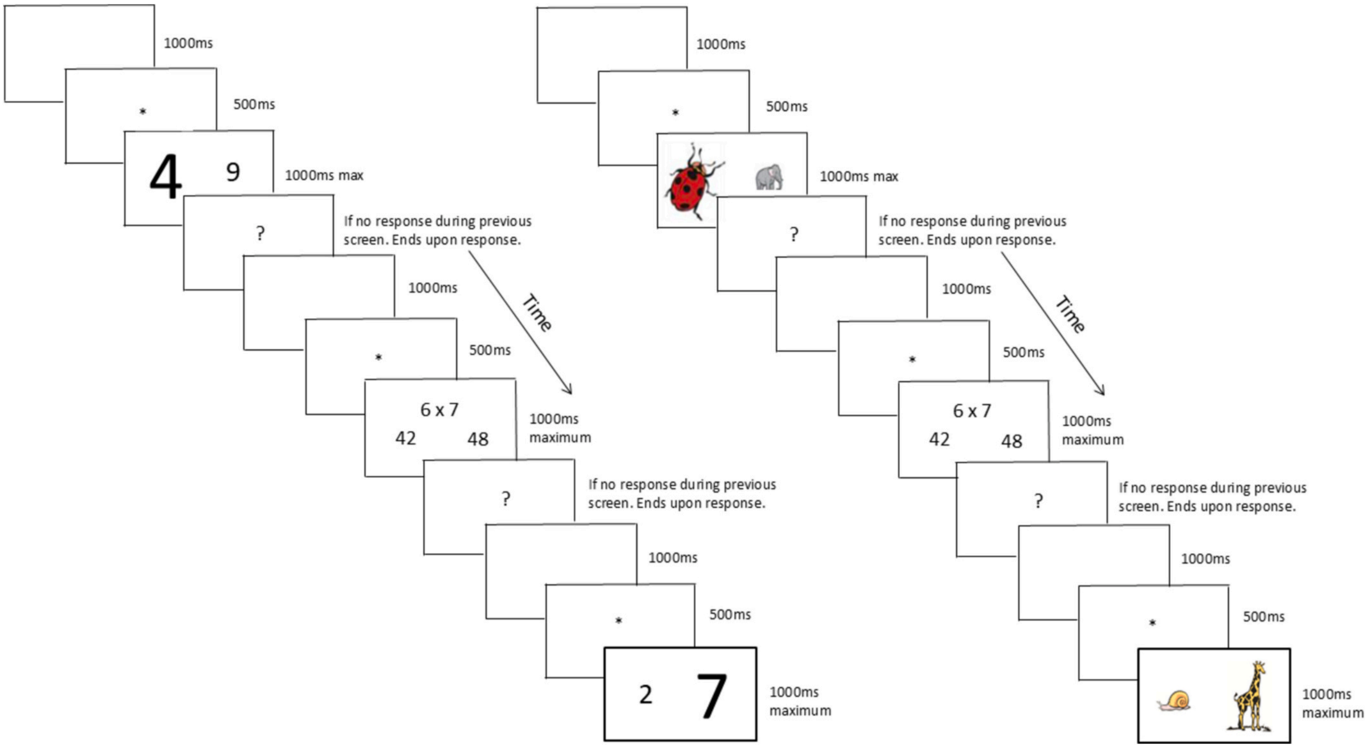

Fig. 1. A sequence of three trials of the interleaved Stroop and multiplication task for the number Stroop condition (left) and the animal Stroop condition (right).

ended upon the participant's response. Participants were asked to respond as quickly and as accurately as they could. At the end of each block participants were presented with their time taken to complete that block in order to motivate them to respond quickly.

Participants first completed 8 trials where they were asked to categorise each number or animal image (depending on which condition they were in) as small or large in real life using the down (small) and up (large) arrow keys. Participants completing the number Stroop task were informed that numbers below 5 were classed small and numbers above 5 were classed as large. They were then presented with 4 trials of number or animal pairs where they were asked to select the stimulus that was larger in real-life, ignoring their physical size on the screen. After this they were presented with 4 multiplication practice trials followed by 4 trials of the interleaved number or animal Stroop and multiplication tasks. Feedback was given on all practice trials but not on experimental trials. Following the practice trials, participants completed four experimental blocks, followed by the non-verbal reasoning screener, four more experimental blocks and finally the multiplication fact screener. The non-verbal reasoning screener was administered half-way through the experimental blocks in order to to break up the task and prevent boredom or fatigue. The experiment took approximately 1 h to complete.

2.1.5. *Analysis plan*

To answer our research questions we conducted 2 × 2 × 2 mixed ANOVAs for accuracy and RT, with Stroop condition (number, animal) as a between-subjects factor, and previous congruence (congruent, incongruent) and current congruence (congruent, incongruent) as within-subjects factors. Median RTs were calculated for each participant for the Stroop and multiplication tasks separately for each condition and then averaged across tasks (as task was not included as a factor in our pre-registered analyses). Evidence that inhibitory control transfers between an established inhibitory control paradigm (Stroop task) and a multiplication fact retrieval task would be indicated by a significant two-way interaction between previous and current congruence. If the transfer of inhibitory control depends on the similarity of the information being processed (i.e. numerical or non-numerical) we would also expect a significant three-way interaction between Stroop condition (number, animal), previous congruence and current congruence. We report Bayesian analyses and equivalence tests where our theoretical interpretations are based on null frequentist effects.

2.2. *Results*

Below we first present the analyses of accuracy and RT data followed by equivalence tests. We focus on reporting the key interaction terms relevant for answering our research questions. Full analyses tables with all results can be found in the Supplementary Material. Bayes Factors were calculated in JASP 0.18.3.0.[2] Twenty one participants were identified as outliers according to our pre-registered criterion (Mahalanobis distance with $p < 0.001$) leaving a final sample of 429 participants for analysis (number Stroop condition: 216; animal Stroop condition: 213).[3]

2.2.1. *Accuracy*

There was a significant interaction between previous and current congruence (F (1, 427) = 82.848, $p < 0.001$, $\eta_p^2 = 0.162$ [CI: 0.112, 0.214], $BF_{10} = 2.781 \times 10^{+13}$, Fig. 2). Bonferroni-corrected post-hoc tests indicated that congruent trials were answered more accurately following a congruent compared to an incongruent trial (CC = 95.3 % [94.9 %, 95.7 %], IC = 94.6 % [94.2 %, 95.0 %], $t = 4.28$, $p_{bonf} < 0.001$, BF_{10} (paired samples t-test) = 76,566.367), whereas incongruent trials were answered more accurately following an incongruent compared to a

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[2] Bayes Factors were calculated with 'legacy options', and compared to a null model. Null models included the simpler terms for the effect of interest. For example, the BF for the 3-way interactions is derived from a null model that includes all 2-way interactions.

[3] We defined outliers based on Mahalanobis distance's derived from eight variables (accuracy and median correct RT for each combination of CC, II, CI and IC trial transitions). We calculated these scores collapsed across both tasks (Stroop and Multiplication) so that the data in the Stroop and Multiplication analyses were derived from the same sample.

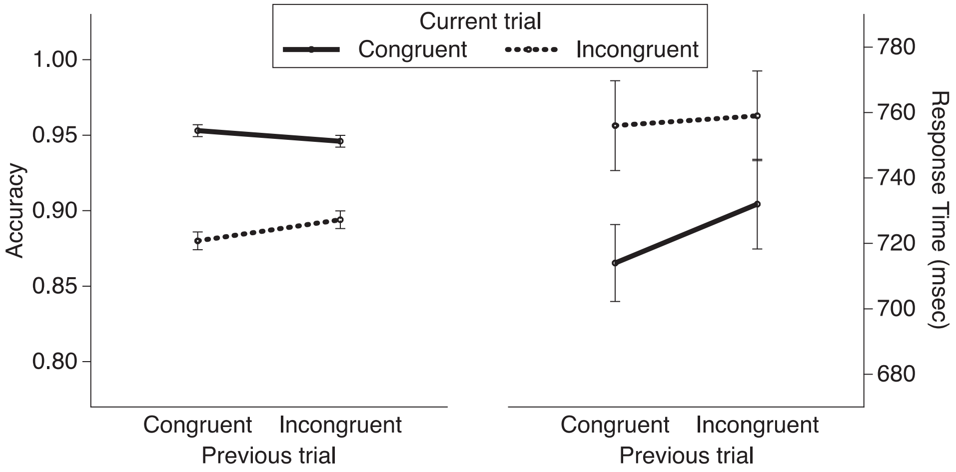

Fig. 2. Mean accuracy (left) and median correct RT (right) for congruent and incongruent trials depending on their previous congruence. Error bars show 95 % confidence intervals.

congruent trial (II = 89.4 % [88.8 %, 89.9 %], CI = 88.0 % [87.5 %, 88.5 %], $t = -9.05$, $p_{\text{bonf}} < 0.001$, BF_{10} (paired-samples t-test) = $5.912 \times 10^{+10)}$. The three-way interaction between Stroop condition, previous congruence and current congruence was not significant (F (1, 427) = 1.215, $p = 0.271$, $\eta_p^2 = 0.003$ [0.000, 0.017]). Bayesian analysis for this three-way interaction provided moderate evidence for the null hypothesis, with a $BF_{10} = 0.164$ compared to a null model that included all the main effects and 2-way interactions. These findings indicate that inhibitory control transferred between the Stroop and multiplication tasks and that there was no difference in this transfer for the number and animal Stroop conditions.

We conducted an exploratory analysis including task (Stroop task, multiplication task), previous congruence, current congruence to investigate the direction of transfer. This revealed that for accuracy data, there was transfer in both directions between the Stroop task and the multiplication task and this transfer was not significantly larger in one direction than the other (see Supplementary Material Table S2 and Fig. S1).

2.2.2. *RT*

There was a significant interaction between previous and current congruence (F (1, 427) = 33.777, $p < 0.001$, $\eta_p^2 = 0.073$ [0.038, 0.116], $BF_{10} > 100$ (71,999.37), Fig. 2). Bonferroni-corrected post-hoc tests indicated that congruent trials were answered more quickly following a congruent compared to an incongruent trial (CC = 714 ms [701 ms, 726 ms], IC = 732 ms [718 ms, 745 ms], $t = -9.732$, $p_{\text{bonf}} < 0.001$, BF_{10} (paired samples t-test) = $4.924 \times 10^{+21}$) whereas the congruency of the previous trial had no impact on RT for incongruent trials (CI = 756 ms [742 ms, 771 ms], II = 759 ms [745 ms, 773 ms], $t = -1.590$, $p_{\text{bonf}} = 0.673$, BF_{10} (paired samples t-test) = 0.154). The three-way interaction between Stroop condition, previous congruence and current congruence was not significant (F (1, 427) = 0.001, $p = 0.970$, $\eta_p^2 < 0.001$ [0.000, 1.00]). Bayesian analysis indicated that there was strong evidence in favour of the null hypothesis for the three-way interaction, with $BF_{10} = 0.114$ compared to a null model that included all the main effects and 2-way interactions. Similarly to the analysis of accuracy, these findings indicate that inhibitory control transferred between the Stroop and multiplication tasks and that there was no difference in this transfer for the number and animal Stroop conditions.

We conducted an exploratory analysis including task (Stroop task, multiplication task), previous congruence, current congruence to investigate the direction of transfer. This revealed that for RT data, there was evidence of transfer from the Stroop task to the multiplication task but not from the multiplication task to the Stroop task (see Supplementary Material Table S4 and Fig. S2).

2.2.3. *Equivalence tests*

To further test the lack of a three-way interaction between Stroop condition, previous congruence and current congruence, we conducted equivalence tests using the Two One-Sided Tests (TOST) procedure (Lakens, 2017). As per our pre-registration, we calculated difference scores to index the congruency sequence effect. For accuracy, the pre-registered difference score was the mean accuracy of the II trials minus the CI trials, and for RT this was the (mean of the) median correct RT of the CI trials minus the II trials. However, as the interaction between previous and current congruence was most evident on current congruent trials for RT, we also conducted an exploratory analysis using the median correct RT of the CC trials minus the IC trials. We conducted equivalence tests comparing these difference scores in the two Stroop conditions. For all equivalence tests, we set our upper and lower boundary to d ± 0.3, so that only small effects would be deemed equivalent (Lakens, 2017). For both accuracy and RT, the difference scores were statistically equivalent between the Stroop conditions and not statistically different (see Supplementary Material). This provides further support that the 2 × 2 interaction between current and previous congruence did not differ between the number and animal Stroop conditions and thus indicating that the transfer of inhibitory control does not depend on the similarity of the information being processed.

2.3. *Discussion*

Experiment 1 addressed our first research question and demonstrated that the congruency sequence effect transfers between an established inhibitory control paradigm (a Stroop task) and a multiplication fact retrieval task. This indicates that inhibitory control is involved in resolving the interference between neighbouring multiplication facts. Moreover this transfer of inhibitory control did not differ depending on whether a numerical or non-numerical Stroop task was performed, addressing our second research question as to whether inhibitory control processes in recalling multiplication facts are stimulus-specific. For accuracy, this transfer was bi-directional between the Stroop task and the multiplication fact retrieval task, but for RT the congruency sequence effect transferred from the Stroop to the multiplication fact retrieval task but not vice-versa. This is likely due to smaller interference effects on the multiplication task for RT than accuracy.

Our third and final research question considers whether the inhibitory control mechanisms involved in multiplication fact retrieval are reactive and transient and/or proactive and sustained. The congruency sequence effect measured in Experiment 1 reflects inhibitory control that is transient and deployed reactively on a trial-by-trial basis. In

Experiment 2 we consider whether the transfer of inhibitory control also extends to list-wide proportion congruency effects that reflect proactive and sustained inhibitory control.

3. Experiment 2

To investigate list-wide proportion congruency effects we adopted another established methodology from the cognitive control literature and manipulated the proportion of congruent and incongruent trials in the number or animal Stroop task, but not on the multiplication fact retrieval task. Transfer would be observed if the proportion of congruent and incongruent trials on the Stroop (inducer) task had an impact on performance on the multiplication (diagnostic) task. More specifically, a list-wide proportion congruency effect would be indicated by a two-way interaction between proportion of congruent trials and congruency. If this is found on both the diagnostic as well as the inducer task this can be taken as evidence of transfer of inhibitory control between the tasks. Following Torres-Quesada et al. (2013), to ensure that any such transfer cannot be explained by a congruency sequence effect driven by the uneven proportions of trial type transitions, we included a final shorter phase of the experiment in which there was an equal proportion of congruent and incongruent trials on both the inducer (Stroop) and diagnostic (multiplication) tasks.

3.1. Method

3.1.1. Participants

370 adults aged 18–30 years (mean = 23.02, SD = 3.65, 271 female, 98 male, 1 with no data provided) participated. This sample size was determined from an a priori power analysis using the Superpower package in R (Lakens & Caldwell, 2021) with effect size estimates from a preparatory study investigating transfer between animal and number Stroop tasks ($N = 60$). A sample size of 370 provides 90.64 % power to detect a 2 × 2 × 2 interaction in accuracy ($\eta_p^2 = 0.034$) and 90.72 % power to detect a 2 × 2 × 2 interaction in RT ($\eta_p^2 = 0.035$), for each Stroop condition separately, at an alpha level of 0.025. The experiment was run online and participants were recruited through Prolific in the same way as Experiment 1. Participants also completed a non-verbal reasoning screener and a multiplication fact screener. Those who performed below our pre-registered criteria on these tasks were excluded from the data analysis and replaced (non-verbal screener, $N = 0$; multiplication fact screener, $N = 15$).

3.1.2. Materials and procedure

There were four between-subjects conditions, created by different combinations of the factors a) proportion (75 % congruent, 75 % incongruent) and b) Stroop condition (number, animal). Participants were assigned to one of the four conditions at random based on their online participant ID.

The task consisted of the number or animal Stroop and the multiplication fact retrieval task, which were created and interleaved as described in Experiment 1. There were two phases to the experiment, a congruency manipulation phase (4 blocks of trials) and an equal congruency phase (2 blocks of trials).

3.1.2.1. Congruency manipulation phase. During the congruency manipulation phase, the proportion of congruent and incongruent trials was manipulated on the inducer (Stroop) task but not the diagnostic (multiplication) task (Table 1). Participants were either presented with 75 % congruent Stroop trials per block (number 75 % congruent and animal 75 % congruent between-subject conditions) or 75 % incongruent Stroop trials per block (number 75 % incongruent and animal 75 % incongruent between-subject conditions).

Table 1
Design of Experiment 2.

Between-subject conditions	Experiment phase	Inducer task (Stroop)	Diagnostic task (multiplication)
75 % congruent (number or animal)	Congruency manipulation	75 % congruent 25 % incongruent	50 % congruent 50 % incongruent
	Equal congruency	50 % congruent 50 % incongruent	50 % congruent 50 % incongruent
75 % incongruent (number or animal)	Congruency manipulation	25 % congruent 75 % incongruent	50 % congruent 50 % incongruent
	Equal congruency	50 % congruent 50 % incongruent	50 % congruent 50 % incongruent

3.1.2.2. Equal congruency phase. In the equal congruency phase the proportion of congruent and incongruent trials on both the inducer and diagnostic task were 50 % for all conditions. As this phase of the experiment was shorter than the congruency manipulation phase we selected 64 multiplication trials from the 128 multiplication problem set described in Experiment 1, ensuring that the related and unrelated problems were matched, on average, for size and parity.

Prior to the congruency manipulation phase, participants completed practice trials in the same way described in Experiment 1, with the exception that the number of intermixed practice trials was increased to 16 (with no option to repeat). Practice trials were 50 % congruent and 50 % incongruent. Following the practice trials, participants completed 4 blocks of 64 trials in the congruency manipulation phase followed immediately by 2 blocks of 64 trials in the equal congruency phase. The same screeners were completed as in Experiment 1. The non-verbal reasoning screener was completed before the practice trials,[4] and the multiplication fact screener after the equal congruency phase.

3.1.3. Analysis plan

To answer our research questions we conducted 2 × 2 x 2 mixed ANOVAs for accuracy and RT with proportion (75 % congruent, 75 % incongruent) as a between-subjects factor, and trial congruence (congruent, incongruent) and task (inducer, diagnostic) as within-subjects factors. Median RTs were calculated for each participant for each task and condition. We performed separate ANOVAs for each Stroop condition (number, animal), in each phase of the experiment (congruency manipulation, equal congruency). Evidence of inhibitory control transfer between the Stroop and multiplication tasks would be indicated by a significant two-way interaction between proportion and trial congruence and the absence of a significant three-way interaction between proportion, trial congruence and task. We report Bayesian analyses where our theoretical interpretations are based on null frequentist effects.

3.2. Results

Below we first present the analyses of accuracy and RT data. We focus on reporting the key interaction terms relevant for answering our research questions. Full analyses tables with all results can be found in the Supplementary Material. Twelve participants were identified as

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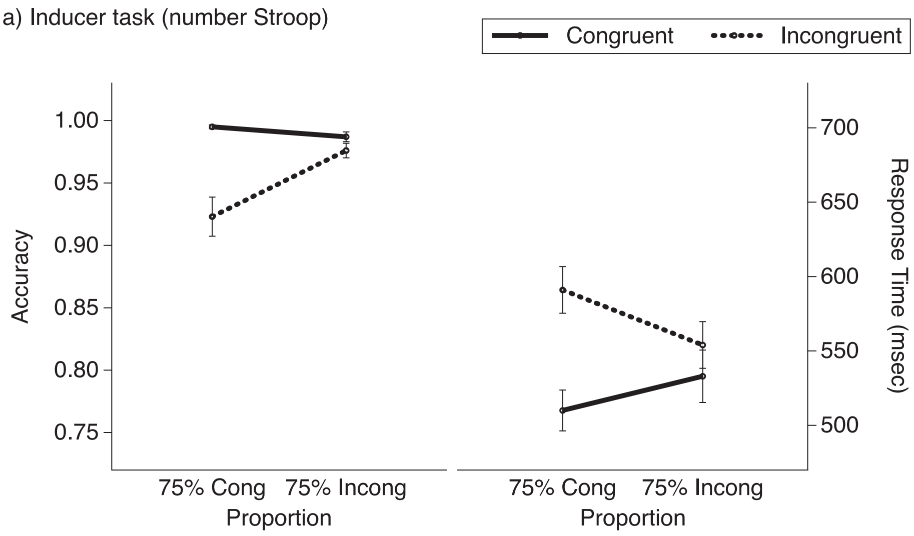
[4] While the nonverbal screener was administered half-way through the experimental blocks in Experiment 1 to break up the task and prevent boredom or fatigue, this was not possible for Experiment 2 as it would have interfered with the transfer of the list-wide proportion congruency effect between blocks of trials.

outliers according to our pre-registered criterion (Mahalanobis distance scores with $p < 0.001$) leaving a final sample of 358 complete datasets for analysis (number Stroop 75 % congruent: 101; number Stroop 75 % incongruent: 83; animal Stroop 75 % congruent: 89; animal Stroop 75 % incongruent: 85).

3.2.1. Congruency manipulation phase

3.2.1.1. Number stroop conditions. For accuracy, there was a significant interaction between trial congruence and proportion, (F (1, 182) = 25.438, $p < 0.001$, $\eta_p^2 = 0.123$ [0.057, 0.198], $BF_{10} = 432.237$), and the three-way interaction between trial congruence, proportion and task was also significant, (Fig. 3; F (1, 182) = 18.075, $p < 0.001$, $\eta_p^2 = 0.090$ [0.034, 0.160], $BF_{10} = 27.178$). Simple main effects analyses found that for the inducer task (number Stroop), there was a significant main effect of trial congruence (C = 99.1 % [98.9 %, 99.3 %], I = 95.0 % [94.1 %, 95.8 %], F (1, 182) = 92.758, $p < 0.001$, $\eta_p^2 = 0.338$ [0.247, 0.417], $BF_{10} = 6.87 \times 10^{+16}$), a significant main effect of proportion (75 %C = 95.9 % [95.3 %, 96.5 %], 75 %I = 98.2 % [97.5 %, 98.8 %], F (1, 182) = 24.001, $p < 0.001$, $\eta_p^2 = 0.117$ [0.053, 0.191], $BF_{10} = 247.251$), and a significant interaction between trial congruence and proportion, (Fig. 3a; F (1, 182) = 50.106, $p < 0.001$, $\eta_p^2 = 0.216$ [0.133, 0.297, $BF_{10} = 5.019 \times 10^{+9}$). In contrast, for the diagnostic task (multiplication) there was a significant main effect of trial congruence, (C = 91.7 % [90.6 %, 92.7 %], I = 80.0 % [78.6 %, 81.5 %], F (1, 182) = 556.65, $p < 0.001$, $\eta_p^2 = 0.754$ [0.705, 0.788], $BF_{10} = 1.798 \times 10^{+54}$), no significant main effect of proportion (75 %C = 87.1 % [85.5 %, 88.7 %], 75 %I = 84.6 % [82.8 %, 86.3 %], F (1, 182) = 4.447, $p = 0.036$, $\eta_p^2 = 0.024$ [0.001, 0.071], $BF_{10} = 1.046$), and no significant interaction between trial congruence and proportion, (Fig. 3b; F = (1, 182) 0.852, $p = 0.357$, $\eta_p^2 = 0.005$ [0.000, 0.035], $BF_{10} = 0.248$). These findings suggest that a list-wide proportion congruency effect was observed in accuracy for the number Stroop task but that this did not transfer to the interleaved multiplication task.

For RT, we found the same pattern of results, with a significant interaction between trial congruence and proportion, (F (1, 182) = 22.736, $p < 0.001$, $\eta_p^2 = 0.111$[0.049,0.185], $BF_{10} = 0.912$, and a significant three-way interaction between trial congruence, proportion and task, (Fig. 3; F (1, 182) = 6.429, $p = 0.012$, $\eta_p^2 = 0.034$[0.004, 0.087], $BF_{10} = 0.196$). Simple main effects analyses found that for the inducer task (number Stroop), there was a significant main effect of trial congruence (C = 521 ms [511 ms, 532 ms], I = 573 ms [561 ms, 584 ms], F (1, 182) = 314.390, $p < 0.001$, $\eta_p^2 = 0.633$[0.565,0.684], $BF_{10} = 9.506 \times 10^{+29}$), no significant main effect of proportion (75 %C = 551 ms [536 ms, 565 ms], 75 %I = 543 ms [527 ms, 559 ms], F (1, 182) = 0.470, $p = 0.494$, $\eta_p^2 = 0.003$[0.00,0.028], $BF_{10} = 0.269$), and a significant interaction between trial congruence and proportion, (Fig. 3a; F (1, 182) = 108.945, $p < 0.001$, $\eta_p^2 = 0.374$[0.284,0.451], $BF_{10} = 1.038 \times 10^{+17}$). In contrast, for the diagnostic task (multiplication) there was a significant main effect of trial congruence, (C = 1036 ms [999 ms, 1073


a) Inducer task (number Stroop)

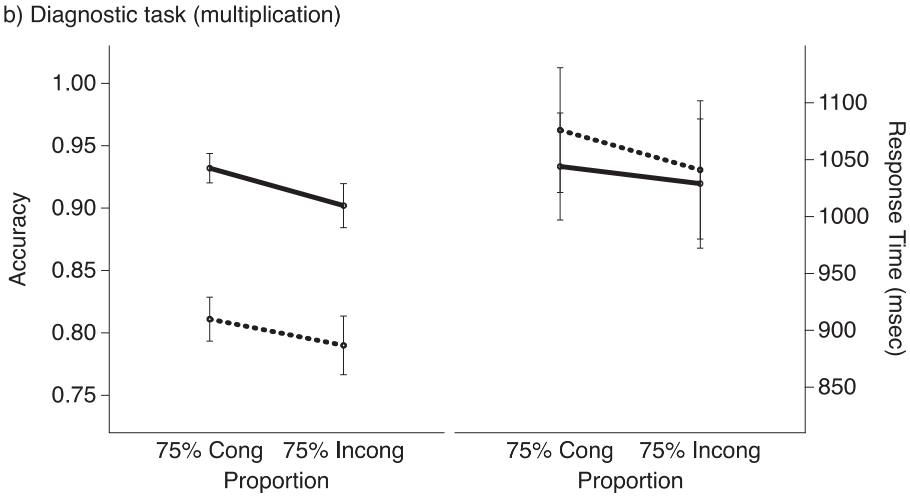

b) Diagnostic task (multiplication)

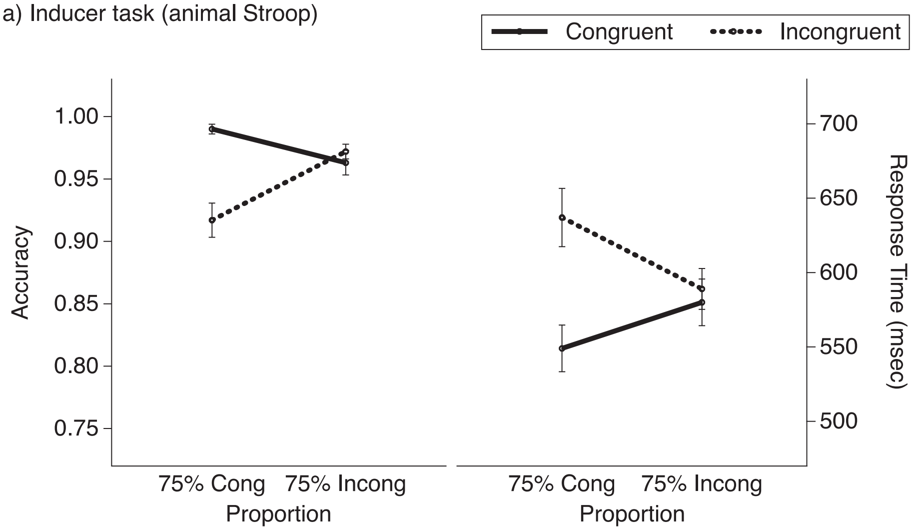
Fig. 3. Accuracy (left) and RT (right) on the inducer (top) and diagnostic (bottom) tasks for the number Stroop conditions in the congruency manipulation phase of Experiment 2. Error bars show 95 % confidence intervals.

ms], $I = 1059$ ms [1017 ms, 1100 ms], $F(1, 182) = 8.499$, $p = 0.004$, $\eta_p^2 = 0.045$[0.008,0.102], $BF_{10} = 9.234$), no significant main effect of proportion (75 %C = 1060 ms [1008 ms, 1111 ms], 75 %I = 1035 ms [978 ms, 1092 ms], $F(1, 182) = 0.398$, $p = 0.529$, $\eta_p^2 = 0.002$ [0.000,0.027], $BF_{10} = 0.501$), and no significant interaction between trial congruence and proportion, (Fig. 3b; $F(1, 182) = 1.57$, $p = 0.212$, $\eta_p^2 = 0.009$[0.000,0.044], $BF_{10} = 0.334$). Consistent with the analysis of accuracy, these findings suggest that a list-wide proportion congruency effect was observed for the number Stroop task but that this did not transfer to the interleaved multiplication task.

3.2.1.2. Animal stroop conditions. For accuracy scores, there was a significant interaction between trial congruence and proportion, ($F(1, 172) = 39.148$, $p < 0.001$, $\eta_p^2 = 0.185$[0.105,0.268], $BF_{10} = 17{,}153.309$), and the three-way interaction between trial congruence, proportion and task was also significant, (Fig. 4; $F(1,172) = 39.36$, $p < 0.001$, $\eta_p^2 = 0.186$[0.105,0.269], $BF_{10} = 3181.466$). Simple main effects analyses found that for the inducer task (animal Stroop), there was a significant main effect of trial congruence (C = 97.7 % [97.2 %, 98.1 %], I = 94.5 % [93.7 %,95.2 %], $F(1, 172) = 60.365$, $p < 0.001$, $\eta_p^2 = 0.260$ [0.170,0.344], $BF_{10} = 3.076 \times 10^{+8}$), a significant main effect of proportion (75 %C = 95.4 % [94.7 %, 96.0 %], 75 %I = 96.8 % [96.1 %, 97.4 %], $F(1, 172) = 8.471$, $p = 0.004$, $\eta_p^2 = 0.047$[0.009,0.107], $BF_{10} = 2.323$), and a significant interaction between congruence and proportion, (Fig. 4a; $F(1, 172) = 97.820$, $p < 0.001$, $\eta_p^2 = 0.363$ [0.270,0.442], $BF_{10} = 2.150 \times 10^{+17}$). In contrast, for the diagnostic task (multiplication) there was a significant main effect of trial congruence, (C = 92.2 % [91.1 %,93.2 %], I = 80.5 % [79.0 %, 81.9 %], $F(1, 172) = 540.04$, $p < 0.001$, $\eta_p^2 = 0.758$ [0.709, 0.793], $BF_{10} = 4.869 \times 10^{+51}$), no significant main effect of proportion (75 %C = 85.7 % [84.1 %, 87.4 %], 75 %I = 86.9 % [85.2 %, 88.6 %], $F(1, 172) = 0.903$, $p = 0.343$, $\eta_p^2 = 0.005$[0.000,0.037], $BF_{10} = 0.219$), and no significant interaction between trial congruence and proportion, (Fig. 4b; $F(1, 172) = 0.201$, $p = 0.654$, $\eta_p^2 = 0.001$[0.000,0.023], $BF_{10} = 0.180$). These findings suggests that a list-wide proportion congruency effect was observed in accuracy for the animal Stroop task but that this did not transfer to the interleaved multiplication task.

For RT, we found a consistent pattern of results, with a significant interaction between trial congruence and proportion, ($F(1, 172) = 25.11$, $p < 0.001$, $\eta_p^2 = 0.127$[0.059, 0.205], $BF_{10} = 0.373$**)**, and a significant three-way interaction between trial congruence, proportion and task, (Fig. 4; $F(1, 172) = 21.563$, $p < 0.001$, $\eta_p^2 = 0.111$[0.047,0.187], $BF_{10} = 0.529$). Simple main effect analyses found that for the inducer task (animal Stroop), there was a significant main effect of trial congruence (C = 565 ms [553 ms, 576 ms], I = 613 ms [601 ms, 625 ms], $F(1, 172) = 267.159$, p < 0.001, $\eta_p^2 = 0.608$[0.535,0.663], $BF_{10} = 3.229 \times 10^{+20}$), no significant main effect of proportion (75 %C = 593 ms [577 ms, 609 ms], 75 %I = 585 ms [568 ms, 601 ms], $F(1, 172) = 0.526$, $p = 0.469$, $\eta_p^2 = 0.003$[0.000,0.031], $BF_{10} = 0.284$), and a

a) Inducer task (animal Stroop)



b) Diagnostic task (multiplication)

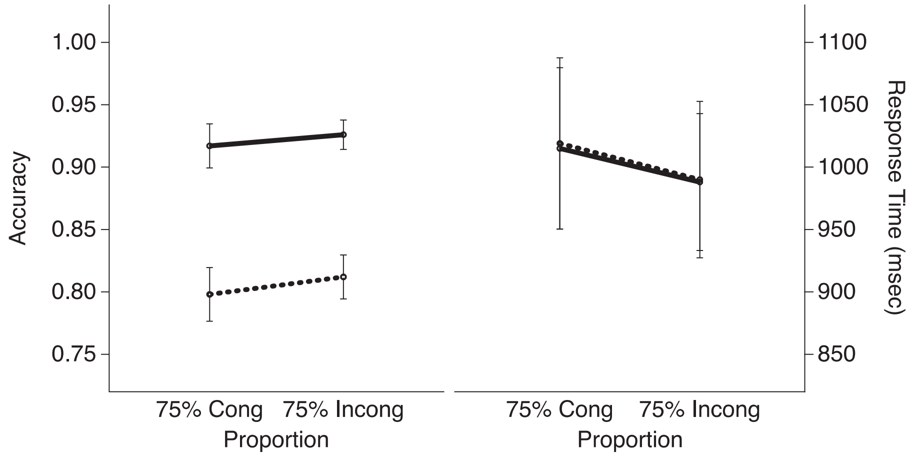


Fig. 4. Accuracy (left) and RT (right) on the inducer (top) and diagnostic (bottom) tasks for the animal Stroop conditions in the congruency manipulation phase of Experiment 2. Error bars show 95 % confidence intervals.

significant interaction between trial congruence and proportion, (Fig. 4a; $F(1, 172) = 175.329$, $p < 0.001$, $\eta_p^2 = 0.505[0.419,0.572]$, $BF_{10} = 3.702 \times 10^{+24}$. For the diagnostic task (multiplication) there was no significant main effect of trial congruence, (C = 1001 ms [958 ms, 1044 ms], *I* = 1005 ms [957 ms, 1052 ms], $F(1, 172) = 0.212$, $p = 0.646$, $\eta_p^2 = 0.001[0.000,0.024]$, $BF_{10} = 0.128$), no significant main effect of proportion (75 %C = 1017 ms [955 ms, 1079 ms], 75 %*I* = 989 ms [925 ms, 1053 ms], $F(1, 172) = 0.387$, $p = 0.535$, $\eta_p^2 = 0.002[0.000,0.028]$, $BF_{10} = 0.538$), and no significant interaction between trial congruence and proportion, (Fig. 4b; $F(1, 172) = 0.014$, $p = 0.905$, $\eta_p^2 < 0.001$ $[0.000,0.007]$, $BF_{10} = 0.206$). Consistent with the analysis of accuracy, these findings suggest that a list-wide proportion congruency effect was observed for the animal Stroop task but that this did not transfer to the interleaved multiplication task.

3.2.2. *Equal congruency phase*

3.2.2.1. Number stroop conditions. For accuracy, there was a significant interaction between trial congruence and proportion, ($F(1, 182) = 5.18$, $p = 0.024$, $\eta_p^2 = 0.028$ $[0.002, 0.077]$, $BF_{10} = 0.494$) but the three-way interaction between trial congruence, proportion and task was not significant, ($F(1, 182) < 1$, *ns,* $BF_{10} = 0.158$). Independent samples *t*-tests indicated that the congruency effect was larger in the 75 % congruent condition (7.1 %) than the 75 % incongruent condition (5.4 %; $t(182) = 2.276$, $p = 0.024$, $BF_{10} = 0.1775$). These findings suggest that a list-wide proportion congruency effect was observed in accuracy for both the number Stroop and the interleaved multiplication task in the equal congruency phase.

For RT, there was a significant interaction between trial congruence and proportion, ($F(1, 182) = 7.71$, $p = 0.006$, $\eta_p^2 = 0.041$ $[0.007, 0.097]$, $BF_{10} = 0.247$), but the three-way interaction between trial congruence, proportion and task was not significant, ($F(1, 182) < 1$, *ns,* $BF_{10} = 0.134$). Independent samples t-tests indicated that the congruency effect was larger in the 75 % congruent condition (390 ms) than the 75 % incongruent condition (200 ms; ($t(182) = 2.776$, $p = 0.006$, $BF_{10} = 5.535$)). These findings suggest that a list-wide proportion congruency effect was observed in RT for both the number Stroop and the interleaved multiplication task in the equal congruency phase.

3.2.2.2. Animal stroop conditions. For accuracy scores, there was no significant two-way interaction between trial congruence and proportion, ($F(1, 172) < 1$, *ns,* $BF_{10} = 0.187$) but the three-way interaction between trial congruence, proportion and task was significant, (Fig. 5; $F(1,172) = 6.539$, $p = 0.011$, $\eta_p^2 = 0.037$ $[0.005, 0.093]$, $BF_{10} = 0.704$). Simple main effects analyses found that for the inducer task (animal Stroop), there was a significant main effect of trial congruence (C = 97.2 % [96.7 %, 97.8 %], *I* = 95.3 % [94.7 %,96.0 %], $F(1, 172) = 32.033$, $p < 0.001$, $\eta_p^2 = 0.157[0.082, 0.238]$, $BF_{10} = 121{,}679.730$), no significant main effect of proportion (75 %C = 96.0 % [95.3 %, 96.6 %], 75 %*I* = 96.6 % [95.9 %, 97.3 %], $F(1, 172) = 1.840$, $p = 0.177$, $\eta_p^2 = 0.011$ $[0.000, 0.049]$, $BF_{10} = 0.353$), and a significant interaction between trial congruence and proportion, ($F(1, 172) = 13.688$, $p < 0.001$, $\eta_p^2 = 0.074[0.023, 0.142]$, $BF_{10} = 78.755$). For the diagnostic task (multiplication) there was a significant main effect of trial congruence, (C = 91.1 % [89.8 %, 92.4 %], *I* = 83.2 % [81.7 %, 84.7 %], $F(1, 172) = 145.407$, $p < 0.001$, $\eta_p^2 = 0.458[0.369, 0.530]$, $BF_{10} = 2.607 \times 10^{+21}$), no significant main effect of proportion (75 %C = 86.7 % [85.0 %, 88.5 %], 75 %*I* = 87.6 % [85.8 %, 89.4 %], $F(1, 172) = 0.467$, $p = 0.495$, $\eta_p^2 = 0.003[0.000, 0.030]$, $BF_{10} = 0.209$), and no significant interaction between trial congruence and proportion, (Fig. 5b; $F(1, 172) = 0.553$, $p = 0.458$, $\eta_p^2 = 0.003$ $[0.000, 0.032]$, $BF_{10} = 0.204$). These findings suggest that a list-wide proportion congruency effect was observed in accuracy for the animal Stroop task but that this did not transfer to the interleaved multiplication task.

For RT, there was no significant interaction between trial congruence and proportion, ($F(1, 172) = 1.202$, $p = 0.274$, $\eta_p^2 = 0.007[0.000, 0.0414]$, $BF_{10} = 0.105$), but a significant three-way interaction between trial congruence, proportion and task, (Fig. 5; $F(1, 172) = 5.939$, p 0.016, $\eta_p^2 = 0.033$ $[0.003, 0.087]$, $BF_{10} = 0.293$). Simple main effect analyses found that for the inducer task (animal Stroop), there was a significant main effect of trial congruence (C = 533 ms [522 ms, 544 ms], *I* = 566 ms [555 ms, 576 ms], $F(1, 172) = 117.272$, $p < 0.001$, $\eta_p^2 = 0.405[0.313, 0.482]$, $BF_{10} = 6.135 \times 10^{+16}$), no significant main effect of proportion (75 %C = 551 ms [53 ms, 565 ms], 75 %*I* = 548 ms [533 ms, 563 ms], $F(1, 172) = 0.059$, $p = 0.809$, $\eta_p^2 < 0.001[0, 0.016]$, $BF_{10} = 0.298$), and a significant interaction between trial congruence and proportion, (Fig. 5a; $F(1, 172) = 18.872$, $p < 0.001$, $\eta_p^2 = 0.099[0.039, 0.173]$, $BF_{10} = 752.412$). For the diagnostic task (multiplication) there was a significant main effect of trial congruence, (C = 887 ms [852 ms, 923 ms], *I* = 904 ms [865 ms, 943 ms], $F(1, 172) = 6.464$, $p = 0.012$, $\eta_p^2 = 0.036[0.004, 0.092]$, $BF_{10} = 2.336$), no significant main effect of proportion (75 %C = 910 ms [859 ms, 962 ms], 75 %*I* = 881 ms [829 ms, 934 ms], $F(1, 172) = 0.611$, $p = 0.436$, $\eta_p^2 = 0.004[0.000, 0.033]$, $BF_{10} = 0.554$), and no significant interaction between trial congruence and proportion, (Fig. 5b; $F(1, 172) = 0.661$, $p = 0.417$, $\eta_p^2 = 0.004$ $[0.000, 0.033]$, $BF_{10} = 0.234$). These findings suggest that a list-wide proportion congruency effect was observed in RT for the animal Stroop task but that this did not transfer to the interleaved multiplication task.

3.3. *Discussion*

Experiment 2 addressed our third research question considering whether the transfer of inhibitory control between an established inhibitory control paradigm (Stroop task) and a multiplication fact retrieval task is reactive and transient and/or proactive and sustained. While the task did induce proactive control, evidenced by transfer of the list-wide proportion congruency effects to the equal congruency phase for the inducer (Stroop) task, we found no evidence that the list-wide proportion congruency effects transferred from the Stroop to multiplication task in the congruency manipulation phase. This was the case when the Stroop task involved processing either numerical or non-numerical information. While there was a suggestion of transfer of the list-wide proportion congruency effect from the number Stroop task to the multiplication task in the equal congruency phase, this is difficult to interpret given the lack of transfer in the congruency manipulation phase.

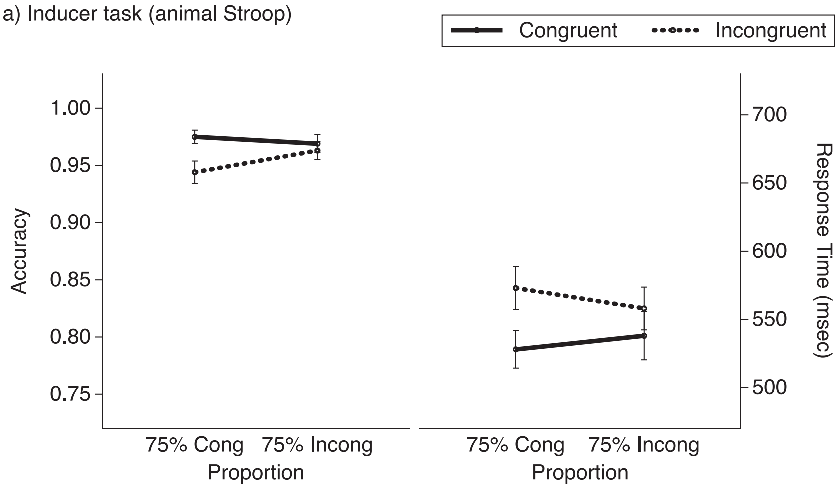
4. General discussion

We carried out two experiments to investigate the role of inhibitory control in multiplication fact retrieval, bringing together questions and methods from the cognitive control and mathematical cognition research literatures. By applying an experimental paradigm in a new context we demonstrated that some types of inhibitory control processes transfer between established inhibitory control tasks and multiplication fact retrieval and this does not differ according to the similarity of the material being processed. Our findings have implications for three main theoretical issues; the role of inhibitory control in multiplication fact retrieval, whether the inhibitory control involved is stimulus-specific, and if it is proactive or reactive in nature. We consider these in turn below. This is followed by discussion of the implications for interventions to improve multiplication fact knowledge.

4.1. *The role of inhibitory control in multiplication fact retrieval*

In Experiment 1 the congruence of a Stroop trial influenced performance on the subsequent multiplication trial and vice-versa, evidenced by a significant two-way interaction between previous and current congruence. Resolving interference on the Stroop trials resulted in more accurate performance on a subsequent multiplication trial that also required resolution of interference; it resulted in less accurate, and slower, performance on a subsequent multiplication trial that did not

a) Inducer task (animal Stroop)



b) Diagnostic task (multiplication)

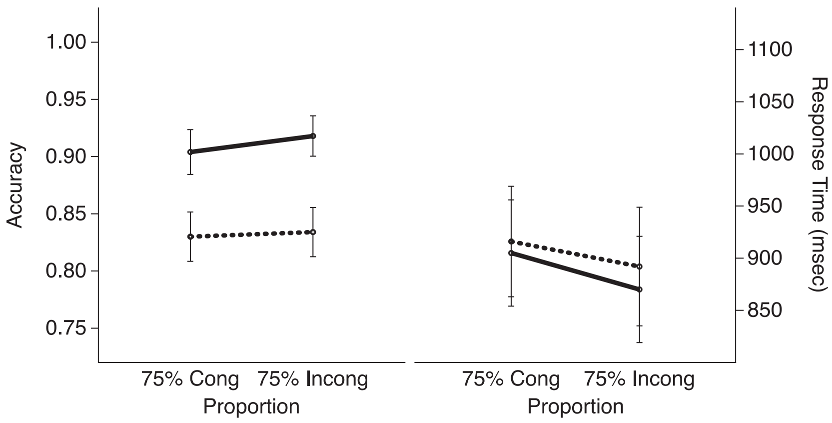


Fig. 5. Accuracy (left) and RT (right) on the inducer (top) and diagnostic (bottom) tasks for the animal Stroop conditions in the equal congruency phase of Experiment 2. Error bars show 95 % confidence intervals.

require resolution of interference. The resolution of interference on a multiplication trial also transferred back to accuracy on the Stroop task. This bi-directional transfer supports the hypothesis that the cognitive processes that are recruited to resolve interference in the Stroop task are also employed to resolve interference between competing answers when retrieving multiplication facts.

The involvement of similar inhibitory control processes in Stroop tasks and retrieval of multiplication facts has implications for theories of number fact retrieval. Theoretical models propose that multiplication facts are stored in an associative network (Ashcraft, 1992; Campbell, 1995; Siegler, 1988; Verguts & Fias, 2005) and, according to several of these models, interference occurs during the retrieval process leading to characteristic patterns of performance and errors (Campbell, 1995; Verguts & Fias, 2005). For example, Campbell (1995) proposes that interference arises from other problems within the network with similar characteristics and magnitudes, while Verguts and Fias (2005) propose that interference arises from neighbouring facts that share an operand. It has previously been proposed that inhibitory control is required to overcome this interference (e.g. Bull & Lee, 2014; Cragg & Gilmore, 2014; Galfano et al., 2011; Megías et al., 2015; Megías & Macizo, 2015, 2016a, 2016b, 2016c). However, evidence from correlational studies for a specific association between inhibitory control and number fact retrieval is mixed (e.g. Bellon et al., 2016; Cragg et al., 2017; Gilmore et al., 2015). Furthermore, findings from negative priming (Megías & Macizo, 2015, 2016a, 2016b, 2016c) and retrieval-induced forgetting phenomena (Galfano et al., 2011; Phenix & Campbell, 2004) remain inconclusive. Here, we find experimental evidence that overcoming interference from related multiplication facts does require a similar form of inhibitory control to that recruited in established inhibitory control paradigms.

We also carried out exploratory drift diffusion modelling (e.g. Myers et al., 2022; Ratcliff, 2006) which decomposes RT and accuracy data into components that reflect evidence accumulation (drift rate) and response caution (boundary separation) as well as non-decision time (see supplementary material for full results). This additional analysis showed that the drift rate, which measures the speed of evidence accumulation, was lower when the participant had to choose between neighbouring facts, i.e. it took them more time to reach the decision threshold, and reduced when the previous trial involved resolving interference compared to when there was no interference on the previous trial. Our findings therefore provide support for those models of multiplication fact retrieval which incorporate interference mechanisms. The current experiments cannot distinguish between the source of this interference (i.e., problems with similar magnitudes vs. neighbouring facts) but our paradigm provides a method for doing so in future research. Nevertheless, our findings suggest that retrieving knowledge of multiplication facts might be difficult for some individuals not because they lack mathematical knowledge of those facts, but because insufficient inhibitory control, or difficulty deploying it, means that they struggle to overcome the interference between multiplication facts. This is consistent with other findings indicating that individuals with high sensitivity to interfering information struggle with multiplication fact retrieval (De Visscher & Noël, 2013, 2014).

Despite indicating that similar inhibitory control processes are required in both Stroop paradigms and multiplication fact retrieval, our experiments cannot determine the precise inhibitory mechanisms involved. Inhibitory control is an umbrella term that covers a range of different mechanisms, including suppression of motor responses or pausing motor output, as well as competitive activation/suppression of competing cognitive processes (e.g. Munakata et al., 2011). It has been suggested that the congruency sequence effect includes both a threshold adjustment process that temporarily halts motor output, as well as a controlled selection process which recruits top-down resources to ensure that the correct target and/or response is selected (Erb & Marcovitch, 2018). This is consistent with findings from the drift diffusion modelling which showed that both evidence accumulation (drift rate) and response caution (boundary separation) processes contributed to the congruency sequence effect.

A further possibility, as indicated by the significant main effect of previous congruence found in our main analyses (see supplementary material) is that our findings reflect an increase in response caution following incongruent trials. We explored this using the drift diffusion modelling. For both the multiplication and Stroop tasks we found an interaction between previous and current congruence in drift rate indicating that evidence accumulation was facilitated by previous incongruent trials, consistent with top-down, cognitive control explanations of the congruency sequence effect. For boundary separation, there was only a significant interaction between previous and current congruence for the Stroop tasks. Moreover, there was no significant main effect of previous congruence for either task. Taken together, this suggests that our findings cannot be simply explained by an increase in response caution following incongruent trials. The fact that the congruency sequence effect on the multiplication task was not evident in the boundary separation parameter may be because participants are aware that there is conflicting information that they need to ignore in the Stroop tasks, and are therefore more cautious in their response, but they are unaware that this is also the case in the multiplication task.

It is possible that there are other non-inhibitory processes that may contribute to the transfer of the congruency sequence effect. Cognitive processes such as working memory have been found to be engaged in Stroop paradigms (e.g. Botvinick et al., 2004; Periáñez et al., 2021), and it is possible that some of these other processes may also be contributing to the transfer of the congruency sequence effect, perhaps in addition to lower-level stimulus-response priming processes (e.g. Hommel et al., 2004). Indeed, the congruency sequence effect was also present on the non-decision time parameter of the drift diffusion modelling, such that participants exhibited shorter non-decision times for congruent trials following congruent trials compared to incongruent trials. This potentially reflects facilitation or inhibition of stimulus encoding and response execution processes contingent on the congruency sequence. More research is required to precisely pinpoint the combination of inhibitory and non-inhibitory mechanisms underpinning the transfer of the congruency sequence effect, further informing our understanding of the cognitive requirements involved in the retrieval of multiplication facts.

Nevertheless, our findings add to the growing literature exploring the role of inhibitory control in mathematics more generally. Suppressing interference between stored facts is one mechanism proposed to explain the broader relationship between inhibitory control and mathematics skills. Other proposed mechanisms include suppressing interference from whole number knowledge when processing rational numbers and suppressing prepotent or inappropriate strategies to make adaptive strategy choices (Borst et al., 2012, 2013; Coulanges et al., 2021; Lemaire & Lecacheur, 2011; Linzarini et al., 2015; Lubin et al., 2013; Van Dooren & Inglis, 2015). To date, theorising on this topic has largely been based on correlational evidence of an association between inhibitory control and overall mathematics achievement (e.g. Blair & Razza, 2007; Bull & Scerif, 2001; Clark et al., 2010; Espy et al., 2004; Merkley et al., 2016; St Clair-Thompson & Gathercole, 2006) as well as specific components of mathematics (e.g. counterintuitive reasoning Brookman-Byrne et al., 2018; rational number understanding: Coulanges et al., 2021; arithmetic fact knowledge and procedural skill: Cragg et al., 2017; strategy choice: Lemaire & Lecacheur, 2011; word problem solving: Winegar, 2013). However this correlational evidence is mixed, with other studies failing to replicate these relationships (e.g. Miller et al., 2013; Monette et al., 2011). Correlational findings provide only limited evidence on which to base theories of the mechanisms underpinning the learning and performance of mathematics. They are able to demonstrate that inhibitory control and mathematics skills are related but are unable to pinpoint how. The experimental paradigm we have used here starts to uncover these precise mechanisms and could be adapted further to directly test which other mathematical processes recruit inhibitory control.

4.2. Is inhibitory control in multiplication fact retrieval stimulus-specific?

Within the cognitive control literature, transfer of inhibitory control, particularly the congruency sequence effect, has primarily been found in situations where the task sets (e.g. Akçay & Hazeltine, 2008; Kiesel et al., 2006), and/or type of conflict (e.g. between stimuli and/or responses; e.g. Akçay & Hazeltine, 2011; Funes et al., 2010a; Wühr et al., 2015) overlap. The task sets and type of conflict used in our tasks differed, therefore it is notable that in Experiment 1 the congruency sequence effect transferred. The two tasks (Stroop, multiplication) differed in a number of ways: In the Stroop tasks the conflict arose primarily between the perceptual and conceptual representations of size, whereas in the multiplication task the conflict arose between competing multiplication facts. The task sets differed in terms of the instructions given (to respond to physical/numerical size, and to select the correct answer to the problem). Moreover, we used two different types of Stroop task, a number Stroop and an animal Stroop, to investigate whether the transfer of inhibitory control depends on the similarity of the stimuli being processed. If the transfer differed depending on the similarity of the stimuli we would expect a significant three-way interaction between previous congruence, current congruence and Stroop condition. This interaction was not significant for either accuracy or RT. Moreover, equivalence tests and Bayes Factors provided support for the null hypothesis. Taken together, these results suggest that there was no difference in the level of transfer of inhibitory control for the two types of Stroop task and that transfer of inhibitory control occurred even when the stimuli used were very different.

Inhibitory control is classically considered as a domain-general mechanism (e.g. Miyake et al., 2000; Norman & Shallice, 1986), however based in part on findings showing the lack of transfer of the congruency sequence effect it has been suggested that there might be multiple inhibitory control mechanisms (Egner, 2008; Notebaert & Verguts, 2008), or more recently, that domain-general processes may be activated in very context-specific ways (Abrahamse et al., 2016; Egner, 2014). This is supported by evidence that congruency sequence effects do not typically transfer between inhibitory control paradigms (Akçay & Hazeltine, 2008, 2011; Funes et al., 2010a; Kiesel et al., 2006; Viarouge et al., 2023; Wühr et al., 2015). Our findings are consistent with a smaller body of research that has showed transfer between an established inhibitory control paradigm (e.g. the Stroop or flanker task) and a distinctively different paradigm such as an implicit bias task (Kleiman et al., 2014), a number conservation task (Linzarini et al., 2015), a bilingual code-switching task or syntactic or perceptual ambiguity tasks (Kan et al., 2013; but see Aczel et al., 2021; Dudschig, 2022). These findings suggest that, in some circumstances, inhibitory control processes can be applied in a similar way across domains, such that transfer can occur. Transfer between very different paradigms has been explained by the suggestion that when tasks differ sufficiently they can both be actively maintained in working memory and transfer of inhibitory control can occur (Braem et al., 2014). The fact that we showed transfer when the tasks used similar stimuli (numbers) as well as very different stimuli (animals) suggests that it is not the similarity of the stimuli that determines whether the tasks are different enough to be simultaneously maintained in working memory or not. Further research is required to fully reconcile the mixed findings in the literature concerning transfer of congruency sequence effects. The time is perhaps right for a meta-analysis to weigh the balance of evidence and systematically explore the factors that influence whether transfer occurs, or not.

The extent to which inhibitory control is recruited in a stimulus- or context-specific manner is also of interest within the field of mathematical cognition. Previous investigations have relied on intervention studies using either general or context-specific inhibitory control tasks (Thorell et al., 2009; Wilkinson et al., 2020) or on comparing the strengths of correlations between mathematics tasks and either numerical or non-numerical inhibitory control tasks (Brookman-Byrne et al., 2018; Bull & Scerif, 2001; Cragg et al., 2017; De Weerdt et al., 2013; Gilmore et al., 2015; Kaufmann et al., 2013; Wang et al., 2012; Winegar, 2013; Zhang & Wu, 2011). These have produced mixed results. Our results provide experimental evidence suggesting that inhibitory control may not always be stimulus-specific and that similar inhibitory control mechanisms can be employed across situations that differ in their stimuli and task demands.

4.3. Is inhibitory control in multiplication fact retrieval proactive or reactive?

A further question of interest to both fields concerns the time-frame over which inhibitory control transfers and the extent to which proactive or reactive mechanisms are involved. In Experiment 1 we showed congruency sequence effects - the transfer of inhibitory control between adjacent/subsequent trials of interleaved Stroop and multiplication fact retrieval tasks with 50 % congruent and incongruent trials. In Experiment 2, while we showed list-wide proportion congruence effects in both the number and animal Stroop (inducer task) in both the congruency manipulation and equal congruency phase, we failed to find evidence for the transfer of list-wide proportion congruency effects: Manipulating the proportion of congruent and incongruent trials on the Stroop (inducer) tasks reduced the size of the congruency effect on the Stroop trials themselves, but did not influence the congruency effect on the interleaved multiplication (diagnostic) task trials. The congruency sequence effect is interpreted as reflecting reactive, transient inhibitory control processes that act on a trial-by-trial basis, whereas the list-wide proportion congruency effect is thought to reflect a proactive sustained deployment of inhibition across a whole task (Braem et al., 2019; De Pisapia & Braver, 2006; Dosenbach et al., 2008;Funes et al., 2010b; Torres-Quesada et al., 2013). While both of these inhibitory control processes might be at play in both the Stroop and multiplication tasks,[5] we found that only the reactive transient processes are similar enough to transfer.

This finding is in contrast to previous studies that have compared the transfer of congruency sequence effect and list-wide proportion congruency effects between Stroop and Simon tasks, which suggest that the sustained, proactive processes indexed by the list-wide proportion congruency effect are more likely to transfer than the reactive, transient processes indexed by the congruency sequence effect (Funes et al., 2010b; Torres-Quesada et al., 2013). A Bayesian model of cognitive control has been put forward that is able to account for flexible adjustments in inhibitory control over changing congruency levels across different time frames that can explain both the congruency sequence effect and list-wide proportion congruency effect within the same model (Jiang et al., 2014). The model predicts the probability of encountering an incongruent trial in order to determine the amount of control that is required. It estimates this probability by combining information from both the previous trial as well as longer-term experience across blocks of trials. In a stable environment, where most of the trials are the same, the weighting is biased to long-term information (i.e. when the majority of trials are either congruent or incongruent). In a more volatile environment when the environment changes rapidly the weighting is biased to shorter-term information. It could be argued that even though in the congruency manipulation phase of Experiment 2 the congruency information is stable, the fact that the task constantly changes results in a weighting biased to shorter-term information, such that the list-wide proportion congruency effect is weakened and does not transfer. Importantly, this model provides an explanation as to why congruency sequence effects were found in Experiment 1, as these are driven by short-term information on the previous trial, but not the list-wide proportion congruency effects in Experiment 2 which rely more heavily on longer-term information.

A further possible explanation as to why proactive control was seen in the Stroop tasks but did not transfer to the multiplication task may be that participants are aware that there is conflicting information they need to ignore in the Stroop tasks and therefore they may be more likely to proactively engage control. In contrast, they may not be aware that there is interfering information present in the multiplication task and therefore not engage control proactively. This hypothesis could potentially be tested by making participants aware of the interference in the multiplication task. A further reason for the difference between studies may be that list-wide proportion congruency effects are more sensitive to differences between stimuli than to the type of conflict (Fernandez-Duque & Knight, 2008; Funes et al., 2010b) and therefore the differences between stimuli in the Stroop and multiplication tasks used in this study was too wide for the transfer of list-wide proportion congruency effects to occur.

4.4. Implications for interventions

Our experimental approach has been able to demonstrate transfer of the congruency sequence effect from an inhibition paradigm to multiplication fact retrieval. This is valuable for identifying the mechanisms underpinning the relationship between inhibitory control and mathematics in order to inform theories of multiplication fact knowledge. Congruency sequence effects within the same task are present in children as young as 5 years of age (Ambrosi et al., 2016). Studies tracking changes in the congruency sequence effect across development either show stability from mid-childhood to adulthood (Cragg, 2016; Erb & Marcovitch, 2018; Larson et al., 2012) or provide tentative evidence that they may reduce slightly with age (Erb & Marcovitch, 2019; Kray et al., 2012; Liu et al., 2018). This suggests that a similar transfer of the congruency sequence effect from inhibition to multiplication fact retrieval would take place in children as well as adults. Nevertheless, this does not mean that educational interventions incorporating standalone inhibitory control training would be beneficial. There has been increasing interest in the potential of inhibitory control training to support children's learning and academic achievement in mathematics and other subjects. However, most attempts to use inhibitory control training to improve academic skills have failed to show significant transfer (Honoré et al., 2020; Thorell et al., 2009). These studies used standalone practice with inhibitory tasks as the training mechanism. Attempts to embed inhibitory control training within lessons using 'stop and think' strategies have been slightly more successful (Wilkinson et al., 2020) although significant transfer was found only in science subjects and not in mathematics. The fact that we found transfer of reactive inhibitory control over a short timescale, but not proactive inhibitory control over a longer timescale, makes it more unlikely that standalone non-mathematical interventions designed to improve children's responses to interference would successfully transfer to mathematical learning situations. Instead, educational approaches that focus on improving children's understanding of the ways in which mathematical material and representations can cause interference (e.g. the interference of

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[5] The use of a predictable task order may have encouraged participants to proactively switch to a different task set after each trial. However, even if proactive transfer does also occur then finding evidence of reactive transfer in Experiment 1 is perhaps even more notable, as a proactive switch would presumably reduce the effects.

whole number knowledge when dealing with rational numbers) may be a better avenue to explore. Critically, while experimental findings such as those reported here can have implications for interventions, it is vital to consider the range of additional factors that come into play when moving from the lab to the classroom, such as the wider classroom context, length and format of the intervention and who it will be delivered by. It is essential to design and test any evidence-based interventions with these in mind.

5. Conclusion

Our research provides experimental evidence that inhibitory control transfers between an established inhibitory control paradigm (Stroop task) and a multiplication fact retrieval task on a trial-by-trial basis. This suggests that similar transient, reactive inhibitory control processes are involved in both retrieving multiplication facts from memory and ignoring irrelevant information in a Stroop task. Our findings have implications for theories of cognitive control and mathematical cognition, but caution should be taken in interpreting the implications for educational interventions.

CRediT authorship contribution statement

Joanne Eaves: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Camilla Gilmore:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Shachar Hochman:** Writing – review & editing, Writing – original draft, Formal analysis. **Lucy Cragg:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Data availability

All data and analysis code created during this research are openly available from the Open Science Framework (OSF) at https://doi.org/10.17605/OSF.IO/ZM4AT.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2024.106054.

References

Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (2016). Grounding cognitive control in associative learning. *Psychological Bulletin*. https://doi.org/10.1037/bul0000047

Aczel, B., Kovacs, M., Bognar, M., Palfi, B., Hartanto, A., Onie, S., … Evans, T. R. (2021). Is there evidence for cross-domain congruency sequence effect? A replication of Kan et al. (2013). *Royal Society Open Science, 8*(3), Article 191353. https://doi.org/10.1098/rsos.191353

Adler, R. M., Valdés Kroff, J. R., & Novick, J. M. (2020). Does integrating a code-switch during comprehension engage cognitive control? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 46*(4), 741–759. https://doi.org/10.1037/xlm0000755

Akçay, Ç., & Hazeltine, E. (2008). Conflict adaptation depends on task structure. *Journal of Experimental Psychology: Human Perception and Performance, 34*(4), 958–973. https://doi.org/10.1037/0096-1523.34.4.958

Akçay, Ç., & Hazeltine, E. (2011). Domain-specific conflict adaptation without feature repetitions. *Psychonomic Bulletin & Review, 18*(3), 505–511. https://doi.org/10.3758/s13423-011-0084-y

Allan, N. P., Hume, L. E., Allan, D. M., Farrington, A. L., & Lonigan, C. J. (2014). Relations between inhibitory control and the development of academic skills in preschool and kindergarten: A meta-analysis. *Developmental Psychology*. https://doi.org/10.1037/a0037493

Ambrosi, S., Lemaire, P., & Blaye, A. (2016). Do young children modulate their cognitive control? *Experimental Psychology, 63*(2), 117–126. https://doi.org/10.1027/1618-3169/a000320

Anderson, M. C., Bjork, R. A., & Bjork, E. L. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 1063–1087. https://doi.org/10.1037/0278-7393.20.5.1063

Ashcraft, M. H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition, 44*(1–2), 75–106. https://doi.org/10.1016/0010-0277(92)90051-I

von Bastian, C. C., Blais, C., Brewer, G., Gyurkovics, M., Hedge, C., Kałamała, P., … Wiemers, E. (2020). Advancing the understanding of individual differences in attentional control: Theoretical, methodological, and analytical considerations. *PsyArXiv*. https://doi.org/10.31234/osf.io/x3b9k

Bellon, E., Fias, W., & De Smedt, B. (2016). Are individual differences in arithmetic fact retrieval in children related to inhibition? *Frontiers in Psychology, 7*. https://doi.org/10.3389/fpsyg.2016.00825

Blair, C., & Razza, R. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647–663.

Blais, C., Robidoux, S., Risko, E. F., & Besner, D. (2007). Item-specific adaptation and the conflict-monitoring hypothesis: A computational model. *Psychological Review, 114*(4), 1076–1086. https://doi.org/10.1037/0033-295X.114.4.1076

Borst, G., Aïte, A., & Houdé, O. (2015). Inhibition of misleading heuristics as a core mechanism for typical cognitive development: Evidence from behavioural and brain-imaging studies. *Developmental Medicine and Child Neurology, 57*(s2), 21–25. https://doi.org/10.1111/dmcn.12688

Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2012). Inhibitory control in number-conservation and class-inclusion tasks: A neo-Piagetian inter-task priming study. *Cognitive Development, 27*(3), 283–298. https://doi.org/10.1016/j.cogdev.2012.02.004

Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2013). Inhibitory control efficiency in a Piaget-like class-inclusion task in school-age children and adults: A developmental negative priming study. *Developmental Psychology, 49*, 1366–1374. https://doi.org/10.1037/a0029622

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624–652. https://doi.org/10.1037/0033-295X.108.3.624

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences, 8*(12), 539–546.

Braem, S., Abrahamse, E. L., Duthoo, W., & Notebaert, W. (2014). What determines the specificity of conflict adaptation? A review, critical analysis, and proposed synthesis. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.01134

Braem, S., Bugg, J. M., Schmidt, J. R., Crump, M. J. C., Weissman, D. H., Notebaert, W., & Egner, T. (2019). Measuring adaptive control in conflict tasks. *Trends in Cognitive Sciences, 23*(9), 769–783. https://doi.org/10.1016/j.tics.2019.07.002

Britton-Drewry, E., Cragg, L., & Gilmore, C. (2022, June). Investigating the types of errors made by children playing an online multiplication production game. In *Mathematical Cognition and Learning Society Conference, Antwerp, Belgium*.

Brookman-Byrne, A., Mareschal, D., Tolmie, A. K., & Dumontheil, I. (2018). Inhibitory control and counterintuitive science and maths reasoning in adolescence. *PLoS One, 13*(6), Article e0198973. https://doi.org/10.1371/journal.pone.0198973

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8*(1), 36–41. https://doi.org/10.1111/cdep.12059

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching and working memory. *Developmental Neuropsychology, 19*(3), 273–293.

Camp, G., Pecher, D., & Schmidt, H. G. (2007). No retrieval-induced forgetting using item-specific independent cues: Evidence against a general inhibitory account. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(5), 950.

Campbell, J. I. D. (1995). Mechanisms of simple addition and multiplication: A modified network-interference theory and simulation. In B. Butterworth (Ed.), *Vol. 1. Mathematical cognition* (pp. 121–164). Psychology Press.

Campbell, J. I. D., & Graham, D. J. (1985). Mental multiplication skill: Structure, process, and acquisition. *Canadian Journal of Psychology/Revue Canadienne de Psychologie, 39*(2), 338–366. https://doi.org/10.1037/h0080065

Chierchia, G., Fuhrmann, D., Knoll, L. J., Pi-Sunyer, B. P., Sakhardande, A. L., & Blakemore, S.-J. (2019). The matrix reasoning item bank (MaRs-IB): Novel, open-access abstract reasoning items for adolescents and adults. *Royal Society Open Science, 6*(10), Article 190232. https://doi.org/10.1098/rsos.190232

Clark, C. A. C., Pritchard, V. E., & Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Developmental Psychology, 46*(5), 1176–1191. https://doi.org/10.1037/a0019672

Coulanges, L., Abreu-Mendoza, R. A., Varma, S., Uncapher, M. R., Gazzaley, A., Anguera, J., & Rosenberg-Lee, M. (2021). Linking inhibitory control to math achievement via comparison of conflicting decimal numbers. *Cognition, 214*, Article 104767. https://doi.org/10.1016/j.cognition.2021.104767

Cragg, L. (2016). The development of stimulus and response interference control in midchildhood. *Developmental Psychology, 52*(2), 242–252. https://doi.org/10.1037/dev0000074

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3*(2), 63–68. https://doi.org/10.1016/j.tine.2013.12.001

Cragg, L., Keeble, S., Richardson, S., Roome, H. E., & Gilmore, C. (2017). Direct and indirect influences of executive functions on mathematics achievement. *Cognition, 162*, 12–26. https://doi.org/10.1016/j.cognition.2017.01.014

De Pisapia, N., & Braver, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing, 69*(10), 1322–1326. https://doi.org/10.1016/j.neucom.2005.12.100

De Visscher, A., Berens, S. C., Keidel, J. L., Noël, M.-P., & Bird, C. M. (2015). The interference effect in arithmetic fact solving: An fMRI study. *NeuroImage, 116*, 92–101. https://doi.org/10.1016/j.neuroimage.2015.04.063

De Visscher, A., & Noël, M.-P. (2013). A case study of arithmetic facts dyscalculia caused by a hypersensitivity-to-interference in memory. *Cortex, 49*(1), 50–70.

De Visscher, A., & Noël, M.-P. (2014). The detrimental effect of interference in multiplication facts storing: Typical development and individual differences. *Journal of Experimental Psychology: General, 143*(6), 2380–2400. https://doi.org/10.1037/xge0000029

De Weerdt, F., Desoete, A., & Roeyers, H. (2013). Behavioral inhibition in children with learning disabilities. *Research in Developmental Disabilities, 34*(6), 1998–2007. https://doi.org/10.1016/j.ridd.2013.02.020

Dignath, D., Johannsen, L., Hommel, B., & Kiesel, A. (2019). Reconciling cognitive-control and episodic-retrieval accounts of sequential conflict modulation: Binding of control-states into event-files. *Journal of Experimental Psychology: Human Perception and Performance, 45*(9), 1265–1270. https://doi.org/10.1037/xhp0000673

Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences, 12*(3), 99–105. https://doi.org/10.1016/j.tics.2008.01.001

Dudschig, C. (2022). Are control processes domain-general? A replication of 'To adapt or not to adapt? The question of domain-general cognitive control' (Kan et al. 2013). *Royal Society Open Science, 9*(7), Article 210550. https://doi.org/10.1098/rsos.210550

Duthoo, W., Abrahamse, E. L., Braem, S., Boehler, C. N., & Notebaert, W. (2014). The congruency sequence effect 3.0: A critical test of conflict adaptation. *PLoS One, 9*(10), Article e110462. https://doi.org/10.1371/journal.pone.0110462

Egner, T. (2008). Multiple conflict-driven control mechanisms in the human brain. *Trends in Cognitive Sciences, 12*(10), 374–380.

Egner, T. (2014). Creatures of habit (and control): A multi-level learning perspective on the modulation of congruency effects. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2014.01247/full

Erb, C. D., & Marcovitch, S. (2018). Deconstructing the Gratton effect: Targeting dissociable trial sequence effects in children, pre-adolescents, and adults. *Cognition, 179*, 150–162. https://doi.org/10.1016/j.cognition.2018.06.007

Erb, C. D., & Marcovitch, S. (2019). Tracking the within-trial, cross-trial, and developmental dynamics of cognitive control: Evidence from the Simon task. *Child Development, 90*(6), e831–e848. https://doi.org/10.1111/cdev.13111

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Developmental Neuropsychology, 26*(1), 465–486. https://doi.org/10.1207/s15326942dn2601_6 [doi]

Fernandez-Duque, D., & Knight, M. (2008). Cognitive control: Dynamic, sustained, and voluntary influences. *Journal of Experimental Psychology: Human Perception and Performance, 34*(2), 340–355. https://doi.org/10.1037/0096-1523.34.2.340

Freitas, A. L., Bahar, M., Yang, S., & Banai, R. (2007). Contextual adjustments in cognitive control across tasks. *Psychological Science, 18*(12), 1040–1043. https://doi.org/10.1111/j.1467-9280.2007.02022.x

Funes, M. J., Lupiáñez, J., & Humphreys, G. (2010a). Analyzing the generality of conflict adaptation effects. *Journal of Experimental Psychology: Human Perception and Performance, 36*(1), 147–161. https://doi.org/10.1037/a0017598

Funes, M. J., Lupiáñez, J., & Humphreys, G. (2010b). Sustained vs. transient cognitive control: Evidence of a behavioral dissociation. *Cognition, 114*(3), 338–347. https://doi.org/10.1016/j.cognition.2009.10.007

Galfano, G., Penolazzi, B., Fardo, F., Dhooge, E., Angrilli, A., & Umiltà, C. (2011). Neurophysiological markers of retrieval-induced forgetting in multiplication fact retrieval. *Psychophysiology, 48*(12), 1681–1691. https://doi.org/10.1111/j.1469-8986.2011.01267.x

Galfano, G., Rusconi, E., & Umiltà, C. (2003). Automatic activation of multiplication facts: Evidence from the nodes adjacent to the product. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*. https://doi.org/10.1080/02724980244000332

Gilmore, C., Keeble, S., Richardson, S., & Cragg, L. (2015). The role of cognitive inhibition in different components of arithmetic. *ZDM, 1–12*. https://doi.org/10.1007/s11858-014-0659-y

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology. General*. https://doi.org/10.1037//0096-3445.121.4.480

Hazeltine, E., Lightman, E., Schwarb, H., & Schumacher, E. H. (2011). The boundaries of sequential modulations: Evidence for set-level control. *Journal of Experimental Psychology: Human Perception and Performance, 37*(6), 1898–1914. https://doi.org/10.1037/a0024662

Hedge, C., Powell, G., & Sumner, P. (2018). The reliability paradox: Why robust cognitive tasks do not produce reliable individual differences. *Behavior Research Methods, 50*(3), 1166–1186. https://doi.org/10.3758/s13428-017-0935-1

Heirdsfield, A. M., & Cooper, T. J. (2004). Factors affecting the process of proficient mental addition and subtraction: Case studies of flexible and inflexible computers. *Journal of Mathematical Behavior, 23*(4), 443–463. https://doi.org/10.1016/j.jmathb.2004.09.005

Hommel, B., Proctor, R. W., & Vu, K.-PhuongL.. (2004). A feature-integration account of sequential effects in the Simon task. *Psychological Research, 68*(1), 1–17. https://doi.org/10.1007/s00426-003-0132-y

Honoré, N., Houssa, M., Volckaert, A., Noël, M.-P., & Nader-Grosbois, N. (2020). Training inhibition and social cognition in the classrooms. *Frontiers in Psychology, 11*. https://doi.org/10.3389/fpsyg.2020.01974

JASP Team. (2021). *JASP (0.14)*.

Jiang, J., Heller, K., & Egner, T. (2014). Bayesian modeling of flexible cognitive control. *Neuroscience & Biobehavioral Reviews, 46*, 30–43. https://doi.org/10.1016/j.neubiorev.2014.06.001

Jonker, T. R., Seli, P., & MacLeod, C. M. (2013). Putting retrieval-induced forgetting in context: An inhibition-free, context-based account. *Psychological Review*. https://doi.org/10.1037/a0034246

Kan, I. P., Teubner-Rhodes, S., Drummey, A. B., Nutile, L., Krupa, L., & Novick, J. M. (2013). To adapt or not to adapt: The question of domain-general cognitive control. *Cognition, 129*(3), 637–651. https://doi.org/10.1016/j.cognition.2013.09.001

Kaufmann, L., Mazzocco, M. M., Dowker, A., von Aster, M., Göbel, S. M., Grabner, R. H., … Nuerk, H.-C. (2013). Dyscalculia from a developmental and differential perspective. *Frontiers in Psychology, 4*. https://doi.org/10.3389/fpsyg.2013.00516

Kazak, A. E. (2018). Editorial: Journal article reporting standards. *American Psychologist, 73*(1), 1–2. https://doi.org/10.1037/amp0000263

Kiesel, A., Kunde, W., & Hoffmann, J. (2006). Evidence for task-specific resolution of response conflict. *Psychonomic Bulletin & Review, 13*(5), 800–806. https://doi.org/10.3758/BF03194000

Kim, S., & Cho, Y. S. (2014). Congruency sequence effect without feature integration and contingency learning. *Acta Psychologica, 149*, 60–68. https://doi.org/10.1016/j.actpsy.2014.03.004

Kleiman, T., Hassin, R. R., & Trope, Y. (2014). The control-freak mind: Stereotypical biases are eliminated following conflict-activated cognitive control. *Journal of Experimental Psychology: General, 143*(2), 498–503. https://doi.org/10.1037/a0033047

Kray, J., Karbach, J., & Blaye, A. (2012). The influence of stimulus-set size on developmental changes in cognitive control and conflict adaptation. *Acta Psychologica, 140*(2), 119–128. https://doi.org/10.1016/j.actpsy.2012.03.005

Lakens, D. (2017). Equivalence tests: A practical primer for T-tests, correlations, and meta-analyses. *Social Psychological and Personality Science, 8*, 355–362. https://doi.org/10.1177/1948550617697177

Lakens, D., & Caldwell, A. R. (2021). Simulation-based power analysis for factorial analysis of variance designs. *Advances in Methods and Practices in Psychological Science, 4*(1). https://doi.org/10.1177/2515245920951503, 2515245920951503.

Larson, M. J., Clawson, A., Clayson, P. E., & South, M. (2012). Cognitive control and conflict adaptation similarities in children and adults. *Developmental Neuropsychology, 37*(4), 343–357. https://doi.org/10.1080/87565641.2011.650337

Lee, K., & Lee, H. W. (2019). Inhibition and mathematical performance: Poorly correlated, poorly measured, or poorly matched? *Child Development Perspectives, 13*(1), 28–33. https://doi.org/10.1111/cdep.12304

LeFevre, J.-A., Bisanz, J., Daley, K. E., Buffone, L., Greenham, S. L., & Sadesky, G. S. (1996). Multiple routes to solution of single-digit multiplication problems. *Journal of Experimental Psychology: General, 125*, 284–306. https://doi.org/10.1037/0096-3445.125.3.284

Lemaire, P., & Lecacheur, M. (2011). Age-related changes in children's executive functions and strategy selection: A study in computational estimation. *Cognitive Development, 26*(3), 282–294. https://doi.org/10.1016/j.cogdev.2011.01.002

Linzarini, A., Houdé, O., & Borst, G. (2015). When stroop helps piaget: An inter-task positive priming paradigm in 9-year-old children. *Journal of Experimental Child Psychology, 139*, 71–82. https://doi.org/10.1016/j.jecp.2015.05.010

Liu, X., Liu, T., Shangguan, F., Sørensen, T. A., Liu, Q., & Shi, J. (2018). Neurodevelopment of conflict adaptation: Evidence from event-related potentials. *Developmental Psychology, 54*(7), 1347–1362. https://doi.org/10.1037/dev0000524

Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*. https://doi.org/10.3758/BF03197535

Lubin, A., Vidal, J., Lanoë, C., Houdé, O., & Borst, G. (2013). Inhibitory control is needed for the resolution of arithmetic word problems: A developmental negative priming study. *Journal of Educational Psychology, 105*(3), 701–708. https://doi.org/10.1037/a0032625

McClelland, J. L., & Rogers, T. T. (2003). The parallel distributed processing approach to semantic cognition. *Nature Reviews Neuroscience, 4*(4), 310–322. https://doi.org/10.1038/nrn1076

Medrano, J., & Prather, R. W. (2023). Rethinking executive functions in mathematical cognition. *Journal of Cognition and Development, 24*(2), 280–295. https://doi.org/10.1080/15248372.2023.2172414

Megías, P., & Macizo, P. (2015). Simple arithmetic development in school age: The coactivation and selection of arithmetic facts. *Journal of Experimental Child Psychology, 138*(Supplement C), 88–105. https://doi.org/10.1016/j.jecp.2015.04.010

Megías, P., & Macizo, P. (2016a). Activation and selection of arithmetic facts: The role of numerical format. *Memory & Cognition, 44*(2), 350–364. https://doi.org/10.3758/s13421-015-0559-6

Megías, P., & Macizo, P. (2016b). The retrieval and selection of arithmetic facts in oral arithmetic. *Acta Psychologica, 170*, 155–162. https://doi.org/10.1016/j.actpsy.2016.08.003

Megías, P., & Macizo, P. (2016c). Simple arithmetic: Electrophysiological evidence of coactivation and selection of arithmetic facts. *Experimental Brain Research, 234*(11), 3305–3319. https://doi.org/10.1007/s00221-016-4728-z

Megías, P., Macizo, P., & Herrera, A. (2015). Simple arithmetic: Evidence of an inhibitory mechanism to select arithmetic facts. *Psychological Research Psychologische Forschung*. https://doi.org/10.1007/s00426-014-0603-3

Merkley, R., Thompson, J., & Scerif, G. (2016). Of huge mice and tiny elephants: Exploring the relationship between inhibitory processes and preschool math skills. *Frontiers in Psychology, 6*. https://doi.org/10.3389/fpsyg.2015.01903

Miller, M. R., Müller, U., Giesbrecht, G. F., Carpendale, J. I., & Kerns, K. A. (2013). The contribution of executive function and social understanding to preschoolers' letter and math skills. *Cognitive Development, 28*(4), 331–349. https://doi.org/10.1016/j.cogdev.2012.10.005

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100.

Monette, S., Bigras, M., & Guay, M.-C. (2011). The role of the executive functions in school achievement at the end of grade 1. *Journal of Experimental Child Psychology, 109*(2), 158–173. https://doi.org/10.1016/j.jecp.2011.01.008

Munakata, Y., Herd, S. A., Chatham, C. H., Depue, B. E., Banich, M. T., & O'Reilly, R. C. (2011). A unified framework for inhibitory control. *Trends in Cognitive Sciences, 15* (10), 453–459. https://doi.org/10.1016/j.tics.2011.07.011

Myers, C. E., Interian, A., & Moustafa, A. A. (2022). A practical introduction to using the drift diffusion model of decision-making in cognitive psychology, neuroscience, and health sciences. *Frontiers in Psychology, 13*. https://doi.org/10.3389/fpsyg.2022.1039172

Neill, W. (1997). Episodic retrieval in negative priming and repetition priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 1291–3105. https://doi.org/10.1037/0278-7393.23.6.1291

Norman, D. A., & Shallice, T. (1986). Attention to action. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.)*, Vol. 4*. *Consciousness and self-regulation: Advances in research and theory* (pp. 1–18). Springer US. https://doi.org/10.1007/978-1-4757-0629-1_1.

Notebaert, W., & Verguts, T. (2008). Cognitive control acts locally. *Cognition, 106*(2), 1071–1080.

OECD. (2013). *OECD skills outlook 2013: First results from the survey of adult skills*. Organisation for Economic Co-operation and Development.

O'Reilly, R. C., Herd, S. A., & Pauli, W. M. (2010). Computational models of cognitive control. *Current Opinion in Neurobiology, 20*(2), 257–261. https://doi.org/10.1016/j.conb.2010.01.008

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Periáñez, J. A., Lubrini, G., García-Gutiérrez, A., & Ríos-Lago, M. (2021). Construct validity of the Stroop color-word test: Influence of speed of visual search, verbal fluency, working memory, cognitive flexibility, and conflict monitoring. *Archives of Clinical Neuropsychology, 36*(1), 99–111. https://doi.org/10.1093/arclin/acaa034

Phenix, T. L., & Campbell, J. I. D. (2004). Effects of multiplication practice on product verification: Integrated structures model or retrieval-induced forgetting? *Memory & Cognition, 32*(2), 324–335. https://doi.org/10.3758/BF03196862

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org.

Ratcliff, R. (2006). Modeling response signal and response time data. *Cognitive Psychology, 53*(3), 195–237. https://doi.org/10.1016/j.cogpsych.2005.10.002

Rothermund, K., Wentura, D., & De Houwer, J. (2005). Retrieval of incidental stimulus-response associations as a source of negative priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(3), 482–495. https://doi.org/10.1037/0278-7393.31.3.482

Rouder, J., & Haaf, J. M. (2019). A psychometrics of individual differences in experimental tasks. *Psychonomic Bulletin & Review, 26*, 452–467. https://doi.org/10.3758/s13423-018-1558-y

Rusconi, E., Galfano, G., Rebonato, E., & Umiltà, C. (2006). Bidirectional links in the network of multiplication facts. *Psychological Research, 70*(1), 32–42. https://doi.org/10.1007/s00426-004-0187-4

Rusconi, E., Galfano, G., Speriani, V., & Umiltà, C. (2004). Capacity and contextual constraints on product activation: Evidence from task-irrelevant fact retrieval. *The Quarterly Journal of Experimental Psychology Section A, 57*(8), 1485–1511. https://doi.org/10.1080/02724980343000873

Siegler, R. S. (1988). Strategy choice procedures and the development of multiplication skill. *Journal of Experimental Psychology: General, 117*(3), 258–275. https://doi.org/10.1037/0096-3445.117.3.258

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *Quarterly Journal of Experimental Psychology, 59*(4), 745–759. https://doi.org/10.1080/17470210500162854. https://doi.org/QR8N57883H862153 [pii].

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science, 12*(1), 106–113. https://doi.org/10.1111/j.1467-7687.2008.00745.x

Tipper, S. P. (1985). The negative priming effect: Inhibitory priming. *The Quarterly Journal of Experimental Psychology, 37A*, 571–590.

Torres-Quesada, M., Funes, M. J., & Lupiáñez, J. (2013). Dissociating proportion congruent and conflict adaptation effects in a Simon–Stroop procedure. *Acta Psychologica, 142*(2), 203–210.

Van Dooren, W., & Inglis, M. (2015). Inhibitory control in mathematical thinking, learning and problem solving: A survey. *ZDM, 47*(5), 713–721. https://doi.org/10.1007/s11858-015-0715-2

Verguts, T., & Fias, W. (2005). Interacting neighbors: A connectionist model of retrieval in single-digit multiplication. *Memory & Cognition, 33*(1), 1–16. https://doi.org/10.3758/BF03195293

Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: Dealing with specific and nonspecific adaptation. *Psychological Review, 115*(2), 518–525. https://doi.org/10.1037/0033-295X.115.2.518

Verguts, T., & Notebaert, W. (2009). Adaptation by binding: A learning account of cognitive control. *Trends in Cognitive Sciences, 13*(6), 252–257. https://doi.org/10.1016/j.tics.2009.02.007

Viarouge, A., Lee, H., & Borst, G. (2023). Attention to number requires magnitude-specific inhibition. *Cognition, 230*, Article 105285. https://doi.org/10.1016/j.cognition.2022.105285

Wang, L.-C., Tasi, H.-J., & Yang, H.-M. (2012). Cognitive inhibition in students with and without dyslexia and dyscalculia. *Research in Developmental Disabilities, 33*(5), 1453–1461. https://doi.org/10.1016/j.ridd.2012.03.019

Weissman, D. H., Jiang, J., & Egner, T. (2014). Determinants of congruency sequence effects without learning and memory confounds. *Journal of Experimental Psychology: Human Perception and Performance, 40*(5), 2022–2037. https://doi.org/10.1037/a0037454

Wendt, M., Kluwe, R. H., & Peters, A. (2006). Sequential modulations of interference evoked by processing task-irrelevant stimulus features. *Journal of Experimental Psychology. Human Perception and Performance, 32*(3), 644–667. https://doi.org/10.1037/0096-1523.32.3.644

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag. https://ggplot2.tidyverse.org.

Wilkey, E. D. (2023). The domain-specificity of domain-generality: Attention, executive function, and academic skills. *Mind, Brain, and Education, 17*(4), 349–361. https://doi.org/10.1111/mbe.12373

Wilkinson, H. R., Smid, C., Morris, S., Farran, E. K., Dumontheil, I., Mayer, S., … The UnLocke Team. (2020). Domain-specific inhibitory control training to improve children's learning of counterintuitive concepts in mathematics and science. *Journal of Cognitive Enhancement, 4*(3), 296–314. https://doi.org/10.1007/s41465-019-00161-4

Williams, C. C., & Zacks, R. T. (2001). Is retrieval-induced forgetting an inhibitory process? *The American Journal of Psychology, 114*(3), 329.

Winegar, K. L. (2013). Inhibition performance in children with math disabilities [UC Riverside]. https://escholarship.org/uc/item/2qx7h3h4.

Wühr, P., Duthoo, W., & Notebaert, W. (2015). Generalizing attentional control across dimensions and tasks: Evidence from transfer of proportion-congruent effects. *The Quarterly Journal of Experimental Psychology, 68*(4), 779–801. https://doi.org/10.1080/17470218.2014.966729

Zhang, H., & Wu, H. (2011). Inhibitory ability of children with developmental dyscalculia. *Journal of Huazhong University of Science and Technology. Medical Sciences, 31*(1), 131–136. https://doi.org/10.1007/s11596-011-0164-2