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Title	Should online maths learning environments be tailored to individuals' cognitive profiles?
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Abstract

Online learning environments are well-suited for tailoring the learning experience of children individually, and on a large scale. An environment such as Math Garden allows children to practise exercises adapted to their specific mathematical ability; this is thought to maximise their mathematical skills. In the current experiment we investigated whether learning environments should also consider the differential impact of cognitive load on children's maths' performance, depending on their individual verbal working memory (WM) and inhibitory control (IC) capacity. Thirty-nine children (8-11 years old) performed a multiple-choice computerised arithmetic game; participants were randomly assigned to two conditions where the visibility of time pressure, a key feature in most gamified learning environments, was manipulated. Results showed that verbal WM was positively associated with arithmetical performance in general, but that higher IC only predicted better performance when the time pressure was not visible. This effect was mostly driven by the younger children. Exploratory analyses of eye-tracking data (N = 36) showed that when time pressure was visible children attended more often to the question (e.g. 6 x 8). In addition, when time pressure was visible, children with lower IC, in particular younger children, attended more often to answer options representing operant confusion (e.g. 9 x 4 = 13) and visited more answer options before responding. These findings suggest that tailoring the visibility of time pressure, based on a child's individual cognitive profile, could improve arithmetic performance, and may in turn improve learning in online learning environments.

Keywords	arithmetic; individual differences; working memory; inhibitory control; eye tracking; time perception
Taxonomy	Developmental Psychology, Educational Psychology, Cognitive Psychology

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Highlights

- The visibility of a time countdown can affect arithmetic performance in children
- Countdown visibility differentially affects attention to question and answer options
- Inhibitory control positively associates with performance when countdown not visible
- Tailoring displays to a child’s cognitive profile may improve arithmetic performance

Abstract

Online learning environments are well-suited for tailoring the learning experience of children individually, and on a large scale. An environment such as Math Garden allows children to practise exercises adapted to their specific mathematical ability; this is thought to maximise their mathematical skills. In the current experiment we investigated whether learning environments should also consider the differential impact of cognitive load on children's maths' performance, depending on their individual verbal working memory (WM) and inhibitory control (IC) capacity. Thirty-nine children (8-11 years old) performed a multiple-choice computerised arithmetic game; participants were randomly assigned to two conditions where the visibility of time pressure, a key feature in most gamified learning environments, was manipulated. Results showed that verbal WM was positively associated with arithmetical performance in general, but that higher IC only predicted better performance when the time pressure was not visible. This effect was mostly driven by the younger children. Exploratory analyses of eye-tracking data (N = 36) showed that when time pressure was visible children attended more often to the question (e.g. 6 x 8). In addition, when time pressure was visible, children with lower IC, in particular younger children, attended more often to answer options representing operant confusion (e.g. 9 x 4 = 13) and visited more answer options before responding. These findings suggest that tailoring the visibility of time pressure, based on a child's individual cognitive profile, could improve arithmetic performance, and may in turn improve learning in online learning environments.

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Title page

Should online maths learning environments be tailored to individuals' cognitive profiles?

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could improve arithmetic performance, and may in turn improve learning in online learning environments.

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Introduction

Extensive individual differences in learning trajectories show that in education there is no such thing as a one-size-fits-all approach. Adaptive e-learning systems, where an online learning environment is continuously adapting to accommodate differences between learners, and changes over time for each individual (Park & Lee, 2003), may help address this challenge and enhance children's success. The idea behind this approach is that if pedagogical procedures are geared to adhere to their individual needs, students will be able to achieve a higher performance more efficiently (for a review, see: Akbulut & Cardak, 2012). One example of such an adaptive e-learning system is Math Garden, an educational tool that adapts the difficulty of the maths problems presented to children aged 4 years and above. The aim of Math Garden is that children always practise maths skills at an appropriate individual level (in the case of Math garden, items are chosen such that the probability of answering correctly is about .75; Jansen et al., 2013; Straatemeier, 2014). In principle, emerging e-learning platforms allow the tailoring of the learning environment to individual students on a large scale. In contrast to the conventional classroom setting where teachers have a good sense of the pupil's individual needs, in an e-learning context explicit information is required to reliably tailor the individuals' learning environment based on these differences. Current adaptive e-learning systems such as Math Garden are well equipped to adapt to the specific maths ability level of the student (Klinkenberg, Straatemeier, & Van Der Maas, 2011). However, the environmental context in online game-based learning environments with its interruptions and distractions poses a risk for the user in terms of sustained attention, engagement, and concentration (Terras & Ramsay, 2012). To maximise the learning potential offered by adaptive e-learning platforms we also need to consider individual differences in the capacities to attend to, process, learn and remember information when designing these technologies (Ramsay & Terras, 2015).

When solving maths problems, the overall load on an individual's cognitive system, also referred to as *cognitive load*, can limit and interfere with performance (Sweller, 1988). This relates particularly to attention and working memory. Working memory (WM) is the ability to control, regulate, and actively maintain relevant information in mind to accomplish complex cognitive tasks, such as mathematical processing (Miyake et al., 2000). Many recent studies propose that individual differences in WM capacity in various domains (verbal, numerical and visuo-spatial) are important predictors of maths achievement (Bull & Lee, 2014; Dumontheil & Klingberg, 2012; Friso-Van Den Bos, Van Der Ven, Kroesbergen, & Van Luit, 2013; Peng, Namkung, & Barnes, 2015; Raghubar, Barnes, & Hecht, 2010). WM can influence maths achievement by helping to keep track of relevant information during problem-solving but is also involved in selecting and switching to the most efficient arithmetic strategy (Barrouillet & Lépine, 2005; Cragg & Gilmore, 2014; Siegler & Lemaire, 1997; Wu et al., 2008). In online game-based learning environments, there is a great risk of overloading a player's working memory due to the rich number of multimedia elements and gamified features, which may limit the capacity for problem-solving (Huang, 2011; Kiili, 2005; Moreno & Mayer, 2003). A cognitive overload on WM capacity may constrain both the acquisition of reasoning skills and the acquisition of knowledge (Baddeley, 1992; Eylon & Linn, 1988).

The cognitive load experienced by an individual depends in part on their ability to selectively attend to relevant stimuli and therefore inhibit their attention to irrelevant stimuli, e.g. distractors. Inhibitory control (IC) is the ability to prevent a response that is not relevant to the current task or situation (i.e. distracting stimuli or thoughts) and to control one's attention, focusing on what we choose and resist interference (Diamond, 2013). IC skills have been found to predict mathematical performance in typically developing children, particularly in pre- and primary school children (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Espy et al., 2004; St Clair-Thompson & Gathercole, 2006). In online game-based learning environments, task-irrelevant distracting stimuli, such as gamified sounds, flashing objects or alternative answer options, can trigger typically-made errors. Similar to the Simon effect (Simon, 1969), where studies have found that irrelevant sensory stimuli in a task directly influence response-selection and increase reaction time, the presence of irrelevant information in an online learning environment could interfere with performance in terms of accuracy and reaction time depending on one's level of IC. Furthermore, Bull et al. (1999) and Rourke (1993) suggest that a lack of inhibitory control is also reflected in the type of errors children tend to make, for example the inability to switch away from addition when multiplication is required (i.e. operant-related error).

Interference and cognitive overload in a learning environment do not always stem from external stimuli, but can also be internal in the form of worries about individual performance or about perceived time pressure (Ashcraft & Kirk, 2001; Mendl, 1999). These stressors can either drive people to use more efficient strategies (i.e. the best speed-accuracy trade-off within the constraints of the new situation) or compete with the attention that is normally allocated to the execution of the task (Caviola, Carey, Mammarella, & Szucs, 2017; Starcke & Brand, 2012). The latter is also known as the adverse effect of 'choking under pressure', where individuals perform worse than if there were no pressure (Baumeister, 1984; Beilock & DeCaro, 2007; Lewis & Linder, 1997). Critically, studies have found that people with high WM capacity are more affected by this dual-task environment and suffer more under pressure than those with low WM capacity (Beilock & Carr, 2005; Sattizahn, Moser, & Beilock, 2016; Wang & Shah, 2014). Additionally, Sattizahn et al. (2016) have found that individuals' variability in attentional control processes influenced the effect of pressure. Those with poor attentional processes suffered decreased performance under pressure, reflecting that some individuals are able to prevent the interfering effect of pressure on their performance, whereas others with poorer attentional control cannot. So, although increased working memory and inhibitory control are generally associated with better maths performance and efficient strategy use, many studies have found that this depends on the stressors in the environment. The purpose of this study was to investigate the impact of stressors in the relatively new context of an online learning environment.

One particular stressor, typical to a lot of online game-based learning environments, is time pressure, which is usually presented in the form of a gamified visual stimulus. For example, in Math Garden there is visual time pressure in the form of coins counting down every second which is also incorporated in the game's scoring rule for maths performance (i.e. "High Speed, High Stakes" rule, see Maris & van der Maas, 2012). The advantage of using time pressure is that it provides the opportunity to relate speed of processing to the ability of the child, which is valuable with easy problems (Klinkenberg et al., 2011; Van Der Maas & Wagenmakers, 2005). Additionally, in the case of games (similar to sports), the challenge of acting within a time limit can make the activity more enjoyable (Freedman & Edwards, 1988). Since time pressure itself is invaluable for most game-based learning environments, the current study addresses a different question: should the visibility of the time pressure (in the form of a countdown) be adapted for individuals, depending on whether it negatively impacts maths performance? Following the interference and overload theory, time pressure in the form of animated visual stimuli could be a distracting component that negatively interferes with solving maths problems, depending on the child's level of IC and WM. However, the alternative situation with no visible reminder of time passing by, requires attention to be allocated to time perception, which could result in suboptimal strategies in speed-accuracy trade-off in the main task (Brown & Perreault, 2017; Grondin, 2010; Matthews & Meck, 2016; Zakay, 1993)

The purpose of this study was threefold. First, we investigated the association of individual differences in verbal WM and IC with performance of simple addition and multiplication problems in blocks of single or mixed operations in a game-based environment for primary school children. We expected that both verbal WM and IC would be positively associated with maths performance, and that higher IC would be associated with a reduced cost of switching between multiplications and additions. Second, we explored whether a particular feature of cognitive load, the visibility of time pressure, would affect arithmetic performance in general and whether this impact was different for children depending on the level of WM and IC. We did not have a hypothesis regarding whether visibility or invisibility of time pressure would be associated with worse maths performance since both features create a dual-task condition. Any effect on maths performance was expected to interact with individual differences in WM and/or IC.

Finally, whether the learner is attending to or actively inhibiting their attention to irrelevant/distracting stimuli can be studied by looking at eye movements and fixations (i.e. moments when the eyes are relatively stationary and fixed on an object) using eye tracking technology (Duprez et al., 2016; Wijnen & Ridderinkhof, 2007). In a learning environment, eye tracking can be used to investigate how learners interact with the stimuli and how the order and duration of their attending affect their problem-solving. Eye tracking data can also be used to improve the learning environment based on knowledge of how learners process the materials through their eye movements (Asteriadis, Tzouveli, Karpouzis, & Kollias, 2009; Barrios et al., 2004). Using eye tracking, we explored differences in the locus of attention during the arithmetic task, depending on whether time pressure was visible or not and the children's levels of WM and IC.

This study included data from a single timepoint, and therefore will not inform our understanding of how individual differences and task features affect learning over time. However, a better understanding of how performance in online maths tasks may be affected by these factors could allow a tailoring of the environment to the individual learner, making sure that the task challenges, and therefore trains, their arithmetic skills rather than loading on other aspects of their cognitive capacity.

Methods

Participants

Forty-two primary school children between 8 and 11 years old were recruited through a local voluntary participant database and through word-of-mouth. Three children were excluded from all analyses because testing sessions were interrupted due to distress or tiredness. The final sample included 39 children (19 male; *M* = 9.60 years old; *SD* = 1.02; range = 8.00-11.50). For three children insufficient eye gaze data were collected, leaving 36 children (18 male; *M* = 9.67 years old; *SD* = 1.00; range = 8.00-11.50) for the eye tracking analyses. The study was approved by the departmental ethics committee at the university. Informed consent was given by caregivers, and verbal assent was given by the participants.

Procedure

All stimuli were presented in Matlab (2017b, MathWorks) using the Psychophysics Toolbox (Brainard, 1997). During the first task, participants performed a maths task on a computer (see Figure 1A) similar in design to Math Garden (Straatemeier, 2014). The study took place in a lab setting and all measures were completed in a single session taking around 30 minutes in total. Before data collection started, condition assignment was randomised for a list of 40 participants using Matlab. Two additional participants were tested to compensate for incomplete or withdrawn participants. There were three randomly ordered blocks comprising, respectively: 20 multiplication problems, 20 addition problems, and 22 mixed multiplication and addition problems. All problems involved single digit numbers between one and nine.

For each arithmetic problem participants were asked to choose one of six answer options, which consisted of the correct answer and the five most frequent errors made by children of similar age on this arithmetic problem, based on Math Garden data previously collected from a large Dutch sample (Figure 1A). Participants had a maximum of eight seconds to click on one of the answers, after which the correct answer was highlighted. In a between-subjects manipulation, 19 children were randomly assigned to the *visible time pressure condition*, where the time limit of eight seconds was visible in the form of coins counting down on the bottom right of the screen, similarly to Math Garden (Figure 1A). The other 20 children had to respond within the same eight seconds, but there were no coins on the screen (*no visible time pressure condition*). After every trial, direct feedback on performance was given: the correct answer was circled in green; additionally, in the case of an incorrect response the incorrect answer was circled in red. The measure of maths performance was calculated with a scoring rule following the equation: $s_{ij} = (2x_{ij} - 1)(d - t_{ij})$ (adapted from Maris & van der Maas, 2012). This rule imposes a speed-accuracy trade-off, where fast and correct responses result in a high score and incorrect responses in a negative score. Player j responds x_{ij} on trial i (x_{ij} = 1 in case of a correct answer, x_{ij} = 0 for incorrect answer) in time t_{ij} (in seconds; range 0:8) before the time limit d (in this study set to 8 seconds) and obtains the score s_{ij} (range -8:8).

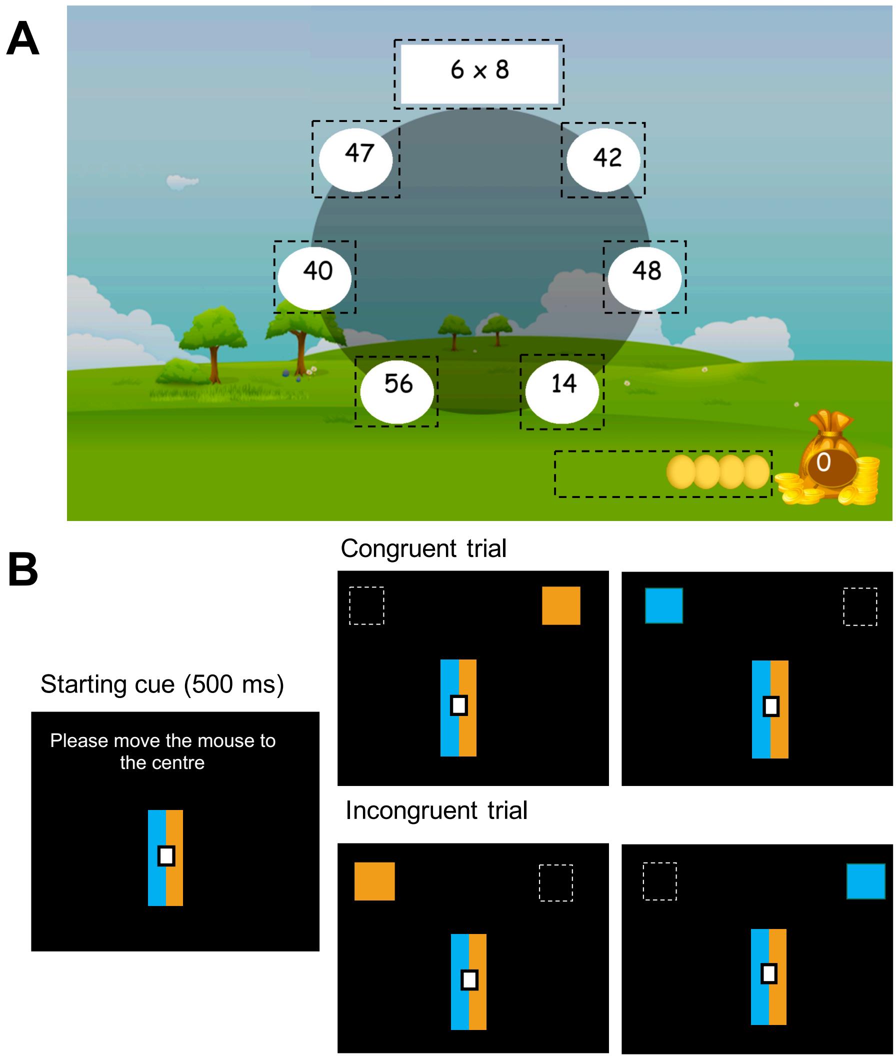

Figure 1. Experimental Tasks. (A) Screenshot of the maths task. Here the problem '6 x 8' is presented at the top of the display with the six answer options underneath. For half of the participants, a visible time pressure was implemented through coins counting down every second. The current total score is depicted in the right bottom corner. The dotted black lines are drawn to represent the areas of interest (AOIs) for the gaze data. **(B)** Setup of the Simon task. A cue indicating the correct colour-response mapping remained on the screen at all time (here indicating that the left box should be clicked for blue target stimuli and the right box for orange target stimuli). Participants first moved their mouse to the centre of the display (small white square). After 500 ms a blue or orange target square stimulus was presented in either top corner of the display. Participants were asked to move their mouse towards and click into the box corresponding to the colour of the target stimulus. On congruent trials the location of the target matched the response associated with the colour of the target (e.g. orange target on

Participants' verbal working memory was then assessed with a backward digit span task, where the children were asked to repeat, backwards, lists of single digit numbers pronounced by the experimenter. After a practice with a list of two numbers, the first level included four lists of three numbers; the child moved one level up (with an additional number) when at least three of the four lists were repeated back successfully. A working memory score was computed as the total number of correct answers.

Inhibitory control was assessed with a computerised spatial incompatibility Simon task (adapted from Duprez et al., 2016; see Figure 1B). Children were asked to move their mouse to either the top left or top right box depending on the colour of the target square while ignoring its location. When the target was blue the children had to move their mouse towards and click into the left box and when it was orange they had to move their mouse towards and click into the right box. In half of the trials the location of the target was congruent with the correct response, in the other half it was incongruent (Figure 1B). Participants completed 40 trials in a randomised order, which resulted in between 1 and 5 trials of the same type (congruent/incongruent) repeated in a row. The measure of inhibitory control, referred to as IC interference effect, was computed as the difference between incongruent and congruent trials mean RT divided by congruent trials mean RT, using correct trials only. A high score reflects a slower RT on incongruent trials (i.e. difficulty in inhibiting their attention to irrelevant information) than congruent trials (i.e. baseline processing speed).

Eye tracking

During the maths and Simon task, the children were seated at a distance of 60 cm in front of an eye tracker. Eye movements were recorded using a Tobii TX300, at a sampling rate of 120 Hz. The raw data were classified into fixations and saccades using the "gazepath" package in R (Team, 2013; van Renswoude et al., 2017). Gazepath uses an algorithm to categorise the data into fixations and saccades while accounting for individual differences and data quality. Fixations in the maths task were labelled as the following three areas of interest (AOIs): (1) the question box, (2) one of the six answer options, or (3) the ‘coins’ (i.e. visible countdown of time; Figure 1A).

Statistical analyses

Data management and statistical analysis were performed using R Software (Team, 2013). For all independent variables *z*-scores were generated to standardise the scores for further analyses. In a first set of analyses, maths performance was averaged over the three blocks (addition, multiplication and mixed block) and compared between the visible time pressure condition and no visible time pressure condition, covarying for age and WM score or IC interference effect, using between-subjects three-way ANCOVAs. With a sample of $N = 39$ the study had 80%, 90% and 95% power to detect large η^2 effect sizes of 0.18, 0.22 and 0.26 respectively when comparing two groups. Eta-square effect sizes have been classified as follows: small $\eta^2 = 0.02$; medium $\eta^2 = 0.13$; large $\eta^2 = 0.26$ (Cohen, 1988). An additional analysis investigated associations between IC and the cost of having to switch between operations. We subtracted the average performance of the mixed block trials from the average performance on the trials in the single operation blocks for multiplication and addition problems separately. These cost measures were entered in ANCOVAs including IC interference effect, visibility of TP and age for multiplication and addition separately. Assumptions of the ANCOVAs were met, with analyses showing homoscedasticity and normality of the residuals.

Eye tracking analyses ($N = 17$ in the visible time pressure condition; $N = 19$ in the no visible time pressure) focused on correct trials (excluding 12.7% of trials) and trials where there was at least more than one fixation to ensure high eye tracking data quality (excluding a further 1.2% of trials). The average number of fixations and the proportional duration of fixation on each AOI were calculated for each participant. An additional metric was the average number of answer option AOIs the participant attended to on a trial. We explored in three-way ANCOVAs whether these eye tracking metrics differed according to the visibility of time pressure and whether this interacted with WM score, IC interference effect or maths performance.

The data were checked for outliers using a criterion of |z-score| > 3 for both the dependent and independent variables. No outliers were identified. In the regression analyses Cook's distance suggested between one and three influential points for some behavioural and eye tracking results. Analyses were repeated excluding these data points and the results were strengthened, except in one case, which is discussed further below.

Additionally, Bayesian ANCOVAs were performed post-hoc for the results with null effects or *p*-values just under the threshold ($p < .05$) using JASP (JASP Team, 2019). To quantify uncertainty about effect size and to obtain evidence in favour of a null hypothesis (Wagenmakers et al., 2018), we distinguished between experimental insensitivity (BF_{10} & $BF_{01} < 3$) and robust support for the alternative hypothesis ($BF_{10} > 3$) or null hypothesis ($BF_{01} > 3$; Dienes, 2014)

RESULTS

RT and accuracy

We performed two one-sided equivalence tests (TOST procedure) with alpha = 0.05 and no assumption of equal variance, and found statistical equivalence between the visible and no visible time pressure group for age, percentage female, verbal WM and IC (Table 1).

T-tests were run to test whether visibility of time pressure associated with maths performance. We did not find any difference between the groups in mean RT, $t(38) = 0.82$, $p = 0.42$, proportion of correct responses, $t(38) = 0.45$, $p = 0.66$, proportion of no response within the time limit, $t(38) = -0.15$, $p = 0.88$, or mean maths score, $t(38) = 0.77$, $p = 0.45$. These comparisons indicate that the visibility of time pressure did not have an effect on maths performance. The average overall maths performance was 3.34 (*SD* = 1.34), meaning that the average score was correct and answered roughly within half of the time limit (see Methods for scoring rule). This measure was used for further analyses.

Table 1 Comparison of the behavioural measures between the visible time pressure (TP) group and the no visible time pressure group. IC: inhibitory control; RT: reaction time; TOST: two one-sided equivalence test; WM: working memory

Variables	**Visible TP (N = 19)**	**No visible TP (N = 20)**	***TOSTs of equivalence***		
	Mean (*SD*)	**Mean (*SD*)**	***95% CI***		***p***
Age	9.46 (0.97)	9.73 (1.08)	-0.28	0.82	0.020
Prop. female	0.58	0.40	-0.09	0.45	<0.001
WM digit score	8.68 (3.42)	8.75 (3.08)	-0.53	0.57	0.002
IC interference effect	0.10 (0.08)	0.09 (0.12)	-0.63	0.46	0.004
RT maths task	4.08 (0.88)	3.85 (0.94)			
Prop. correct maths task	0.81 (0.16)	0.83 (0.17)			
Prop. no response maths	0.09 (0.08)	0.08 (0.11)			
Maths score	3.19 (1.34)	3.48 (1.35)			

Mean accuracy in the Simon task was high (M = .99, SD = .05). As expected, RTs differed between congruent and incongruent trials, $t(38) = 6.17$, $p < 0.001$. Participants were on average 150 ms slower in incongruent trials (Figure 2A). The individual average IC interference effect was used as a measure of inhibitory control for further analyses (Figure 2B).

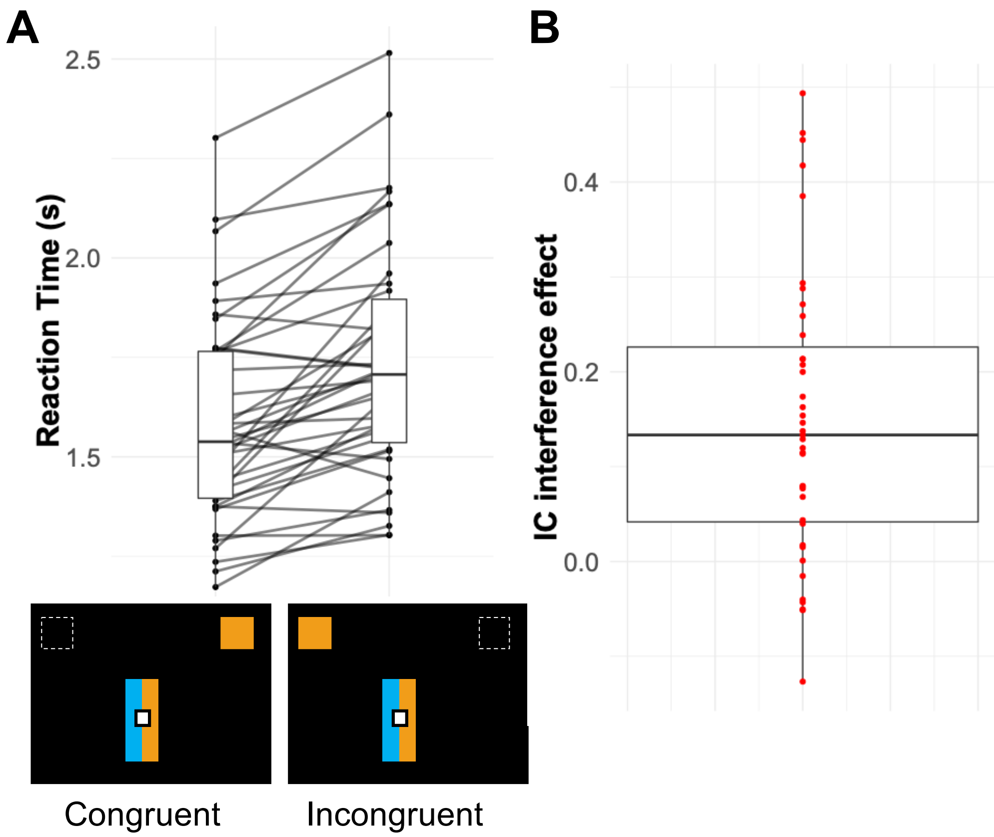

Figure 2. Interference effect on reaction time (RT) in the Simon task of inhibitory control (IC). (A) Boxplots of individual mean RTs as a function of trial type (congruent vs. incongruent). **(B)** Boxplot of the IC interference effect, calculated as the difference between the incongruent and congruent trials mean RT divided by congruent trials mean RT for correct trials only.

Impact of time pressure on maths performance depending on the level of IC and verbal WM

The first analysis included only age and visibility of time pressure (TP) as predictors of maths performance. This showed a positive association between age and maths performance, $F(1, 35) = 32.05$, $p < 0.001$, $\eta_p^2 = 0.53$ but not TP ($p = 0.892$, $\eta_p^2 = 0.00$) nor was there an interaction between age and TP ($p = 0.679$, $\eta_p^2 = 0.01$). The second analysis included WM score as a covariate (Table 2). WM score was positively associated with maths performance ($F(1,31) = 13.15$, $p = 0.001$, $\eta_p^2 = 0.24$; Figure 3A) but there was no interaction with age nor TP (all p's > 0.50, $\eta_p^2 < 0.01$). The Bayesian ANCOVA showed that a null model with merely main effects for WM score and age was 11.4 times more likely than including any of the above-mentioned interactions or the main effect of time pressure.

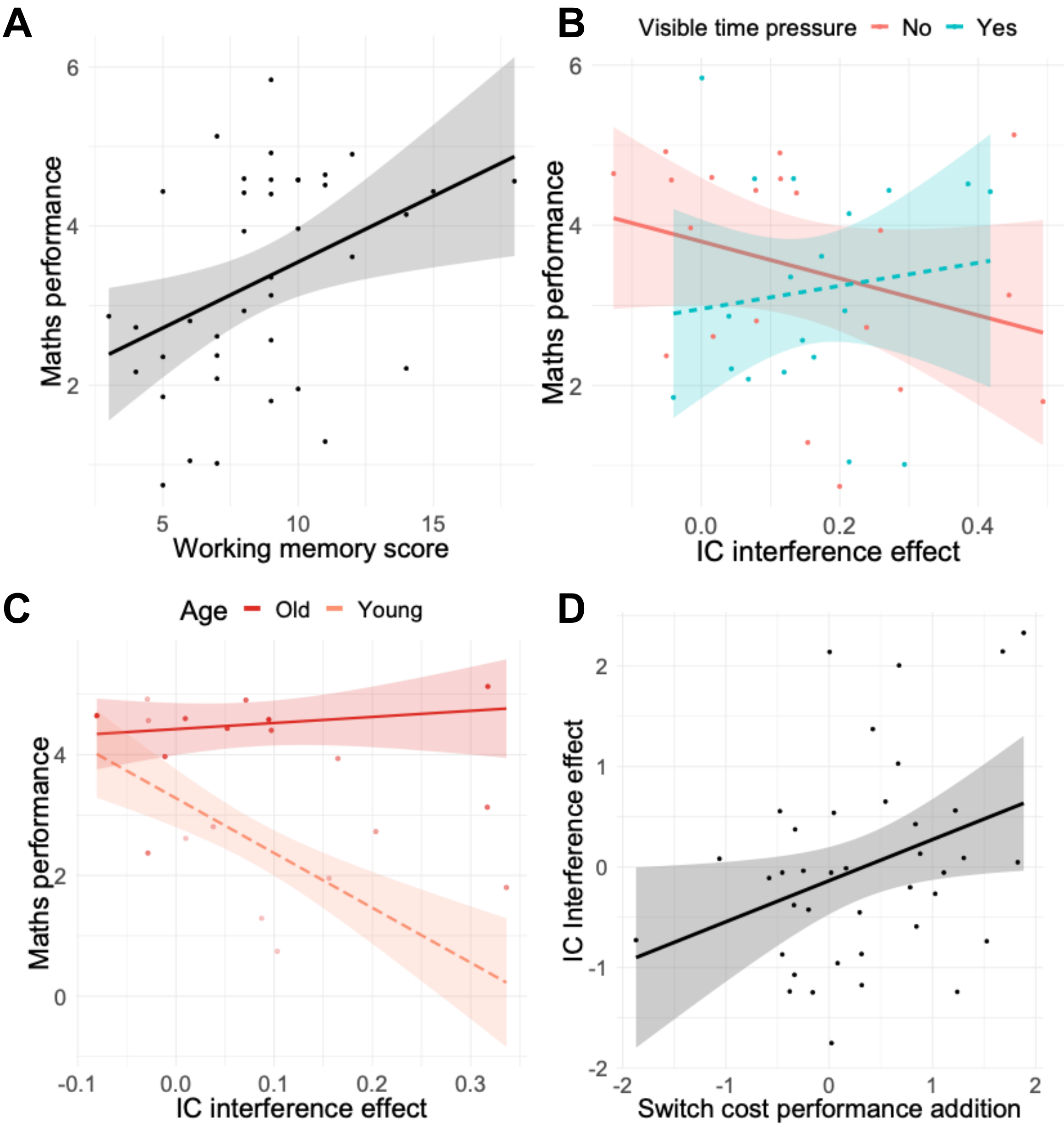

Figure 3. Maths performance (combined accuracy and reaction time score) as a function of verbal working memory (WM) score and inhibitory control (IC) interference effect. (A) WM score was positively associated with maths performance. **(B)** The association between maths performance and IC interference effect depended on the visibility of the time pressure. **(C)** Graph illustrating the age x IC interference effect interaction on maths performance for the no visible time pressure group. A median split was performed for age showing two regression lines for young (8-9.5 yr) and old age (9.5-11.5 yr), but note that age was treated as a continuous variable in the analyses. **(D)** The cost of mixing operations on performance of the addition problems (mixed operations block score – single operation block score) was positively predicted by the IC interference effect.

The third analysis (Table 2) included the IC interference effect as covariate. There was no main effect of IC interference effect, $p = 0.62$, $\eta_p^2 = 0.01$, but there was a significant two-way interaction between TP and IC interference effect, $F(1,31) = 6.59$, $p = 0.015$, $\eta_p^2 = 0.18$, and a three-way interaction between TP, age and IC interference effect on maths performance, $F(1,31) = 4.55$, $p = 0.041$, $\eta_p^2 = 0.13$. Significant evidence for both interaction effects were demonstrated through Bayesian analyses (Table 2).

Table 2: Summary of the effects observed in the ANCOVAs of the behavioural and eye tracking data. Effect sizes of significant effects (p's < .05) are reported. Cases were robust support (BF > 3) for the alternative or the null hypothesis was provided by the Bayesian ANCOVAs are indicated with a [B]. Hyphens indicate the main effect or interaction was not significant but there was no strong evidence in support of the null hypothesis. TP = time pressure; WM = working memory; IC = inhibitory control.

Verbal working memory	**Age**	**TP**	**WM**	**Age x TP**	**WM x TP**	**WM x TP x Age**
1. Behavioural data[a]						
Maths performance	$\eta_p^2 = 0.53$[B]	null[B]	$\eta_p^2 = 0.24$[B]	null[B]	null[B]	null[B]
2. Eye tracking data (number of fixations)[b]						
Question box	-	$\eta_p^2 = 0.15$[B]	-	-	-	-
Answer options	null[B]	null[B]	null[B]	null[B]	null[B]	null[B]

Inhibitory control	**Age**	**TP**	**IC**	**Age x TP**	**IC x TP**	**IC x TP x Age**
1. Behavioural data[a]						
Maths performance	$\eta_p^2 = 0.53$[B]	null[B]	null[B]	null[B]	$\eta_p^2 = 0.18$[B]	$\eta_p^2 = 0.13$[B]
Operation switch cost on multiplication problems	null[B]	null[B]	null[B]	null[B]	null[B]	null[B]
Operation switch cost on addition problems	-	-	$\eta_p^2 = 0.13$	-	-	null[B]
2. Eye tracking data (number of fixations)[b]						
Question box	-	$\eta_p^2 = 0.15$[B]	-	-	-	-
Operation errors on multiplication problems	-	null[B]	-	-	$\eta_p^2 = 0.16$[B]	-
Operation errors on addition problems	-	null[B]	-	-	-	-
Answer options	-	-	-	-	$\eta_p^2 = 0.13$	-

[a] df = 31, [b] df = 28

To examine the two-way and three-way interactions, separate multiple regressions were performed in the *visible time pressure* and *no visible time pressure* groups. In the group with visible time pressure, the IC interference effect and age x IC interference effect interaction terms did not significantly predict variance in maths performance (Figure 3B; BF_{01} = 0.57, i.e. no evidence for either hypotheses). In contrast, the group with no visible time pressure showed a negative association between maths performance and IC interference effect (β = -0.42, $t(16)$ = 2.77, p = 0.014; BF_{10} = 6.47, i.e. substantial evidence for including this effect; Figure 3B), and an interaction between age and IC interference effect (β = 0.43, $t(16)$ = 2.629, p = 0.018; BF_{10} = 8.84). The interaction effect showed that the association between maths performance and IC interference effect was mostly driven by the younger children (Figure 3C).

Operation switch cost

To investigate whether switching between operations led to a cost in performance, we compared the mean maths scores of single operation vs mixed operations blocks for multiplication and addition problems separately. Paired *t*-tests showed that children's performance on multiplication problems did not differ between the mixed (M = 2.83) and single operation multiplication blocks (M = 2.76), $t(38)$ = 0.41, p = 0.341. For addition, children performed less well on the trials in the mixed block (M = 3.67) than in the single operation blocks (M = 4.00), $t(38)$ = 2.51, p = 0.008. Therefore, children showed a cost of having to switch between multiplication and addition on addition problems only.

Since the ability to switch between arithmetic operations has been associated with inhibitory control in previous studies (Bull et al., 1999; Rourke, 1993), additional analyses explored whether IC predicted the ability to switch between addition and multiplication operations in the mixed blocks compared to the single operation blocks (Table 2). For the addition problems the IC interference effect predicted the performance difference between the mixed and single operation blocks, $F(31,1) = 5.06$, $p = 0.031$, $\eta_p^2 = 0.13$. Bayesian ANCOVA showed that a model including IC was 2.68 times more likely than the null model; no interaction with age ($p = 0.302$, $\eta_p^2 = 0.03$) or TP ($p = 0.153$, $\eta_p^2 = 0.06$) was found.

Eye fixations and patterns

Exploratory analyses investigated whether eye movements during the maths task could give some insight into the behavioural findings. Analyses were performed on the mean number of fixations and proportion of total fixation duration on specific AOIs. The latter did not show any significant effect.

The first analyses looked at the fixations on the question box AOI (e.g. 6 x 8 on Figure 1A), since other studies have found that looking back and forth at the question is positively associated with attentional and working memory load (Droll & Hayhoe, 2007; Orquin & Mueller Loose, 2013). ANCOVAs were run to test for associations with the visibility of time pressure in interaction with individual differences in IC and WM separately, while covarying for age and maths performance (Table 2). A significant main effect for TP, $F(1,28) = 12.02$, $p = 0.003$, $\eta_p^2 = 0.43$ (BF_{10}=30.88, i.e. very strong evidence), showed that there were more fixations on the question box when time pressure was visible (M = 2.69) than when there was no visible time pressure (M = 2.02; Figure 4A).

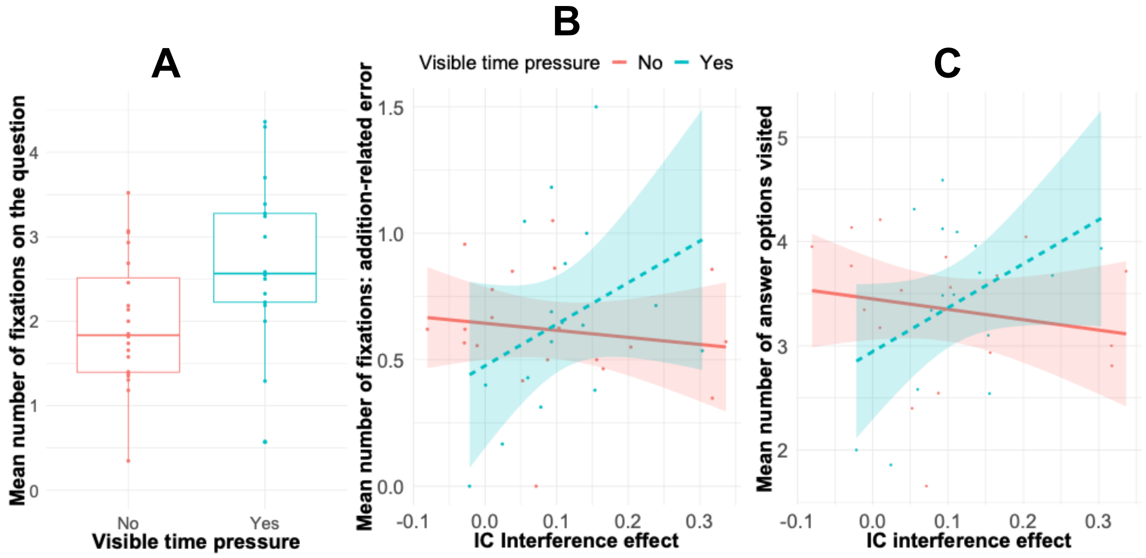

Figure 4. Eye tracking metrics showing significant associations with the visibility of time pressure and the inhibitory control (IC) interference effect. (A) The average number of fixations on the question box was higher in the visible time pressure group compared to the no visible time pressure group. **(B)** The mean number of fixations on addition-related errors was positively associated with the IC interference effect in the visible time pressure group only. **(C)** The mean number of attended answer options was positively associated with the IC interference effect when the time pressure was visible.

Secondly, since operation-related errors have been found to be associated with the level of IC (Bull et al., 1999; Rourke, 1993), fixations on the operation-related error answer options were investigated separately for addition and multiplication. ANCOVAs were performed to test for associations with the visibility of time pressure and the IC interference effect, covarying for age and maths performance. For the addition problems with multiplication-related errors as answer options, we found no significant predictors (p's > 0.20; $\eta_p^2 < 0.05$, Table 2). For multiplication problems with addition-related errors a significant interaction between TP and IC interference effect, $F(1,28) = 5.34$, $p = 0.018$, $\eta_p^2 = 0.44$ (BF_{10}= 5.21, i.e. substantial evidence) showed that the mean number of fixations on the addition-related error increased with increasing IC interference effect (β = 0.56) only when time pressure was visible.

Finally, analyses were performed to investigate the mean number of answer options participants looked at before giving their answer, and whether this related to WM, IC and the visibility of time pressure. An ANCOVA was performed with the average number of answer options attended to as the dependent variable, visibility of time pressure and IC interference effect or WM as independent variable, and age and maths performance as covariates. The analysis with WM as a predictor showed no main or interaction effects, but only evidence that a null model was 11 times more likely than including any of the predictors. The analysis with IC as a predictor showed a significant interaction between visibility of time pressure and IC interference effect, $F(1,31) = 4.60$, $p = 0.039$, $\eta_p^2 = 0.13$. However, Cook's distance highlighted there was one influential point that drove this interaction. Consistent with this, only anecdotal evidence ($BF_{10} = 2.90$) for including this interaction to the null model was found in the Bayesian regression (Figure 4C & Table 2). Follow-up regression analysis showed a trend for a positive association for IC interference effect when time pressure was visible ($\beta = .54$, $t(13) = 2.03$, $p = 0.063$) but little evidence ($BF_{10} = 1.23$) in the Bayesian regression. No association between the IC interference effect and the number of answer options visited was found when time pressure was invisible ($\beta = -.21$, $t(16) = 0.82$, $p = 0.423$; Bayesian regression showed anecdotal evidence for null hypothesis, $BF_{01} = 2.00$).

Discussion

This study combined behavioural and eye tracking measures to test whether individual differences in verbal working memory and inhibitory control in primary school children could predict their ability to solve arithmetic problems in different online learning environments, where visibility of time pressure was varied. The behavioural results showed that verbal working memory was a positive predictor of arithmetic performance in general, in line with previous studies (see Raghubar et al., 2010 for a review), and that this association was independent of the visibility of time pressure. In contrast, individual differences in inhibitory control only predicted arithmetic performance when the same time pressure was not visibly illustrated by an animation. Additionally, we found that this association with inhibitory control was mostly driven by the younger children, similar to previous studies (Bull & Scerif, 2001). Eye tracking results also showed that the children fixated on different parts of the stimuli during the maths task depending on the visibility of time pressure, their IC level and age.

Overall, these findings point out that the visibility of time pressure may affect performance of certain individuals in online learning environments, and that possible constraints of attentional control (i.e. the amount of interfering information compromising cognitive resources) should be considered. Learning environment with both visible and invisible time pressure can create dual-task environments leading to less attention to the main task of solving maths problems. When time pressure is visible, the user has a constant physical reminder of timing, i.e. in this study in the form of an animated visual stimulus. Adding more visual stimuli and time pressure is suggested by previous studies to contribute to loading working memory capacity, leading to suboptimal strategies and attention (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Caviola et al., 2017; Terras & Ramsay, 2012). This impact can also be influenced by other individual differences such as maths anxiety (Ashcraft & Krause, 2007; Caviola et al., 2017; Kellogg, Hopko, & Ashcraft, 1999), engagement and attitude to learning (Barkatsas, Kasimatis, & Gialamas, 2009; Kebritchi, Hirumi, & Bai, 2010). Although the visibility of time pressure did not interact with individual differences in verbal WM in terms of maths performance, the notion of visible time pressure as an increasing demand on working memory resources is reflected in our eye tracking results. Children made more fixations on the question in the visible than in the invisible time pressure condition, suggesting that they may have found it more difficult to keep the question in their mind (Orquin & Mueller Loose, 2013). Although previous studies suggested that the impact of extra stressors on maths performance depends on the ability to resist distractions (i.e. inhibitory control; Sattizahn et al., 2016), we showed that the performance of children was not affected by their level of inhibition when time pressure was visible. The higher number of fixations on answer options and on operation-related errors did suggest that for children with lower IC the task was more demanding in terms of decision difficulty and/or attentional resources (Orquin & Mueller Loose, 2013), but this did not result in lower performance.

Time perception is intensively studied (for an overview of recent reviews, see Block, Grondin, & Gibbon, 2014) and involves diverse perceptual, motor, cognitive and brain processes (Block & Gruber, 2014). One line of investigation in time perception concerns its bidirectional interference with higher-level executive cognitive processes such as mental arithmetic but also with executive functions (Block, Hancock, & Zakay, 2010; Brown, Collier, & Night, 2013). This interference occurs in a dual-task condition where time perception competes for the same attentional resources as the other task, leading to cognitive load. Since the interference is bidirectional, studies have also shown that lower inhibitory control is associated with less accurate time perception (Brown & Perreault, 2017; Meaux & Chelonis, 2005). This closely aligns with our finding that low levels of inhibitory control were associated with low arithmetical performance when the children also had to estimate time without a reminder. This could be due to an impairment of time perception, such that these children have trouble deciding on an optimal speed-accuracy trade-off strategy. Therefore, for children with low inhibitory control, visualising time pressure could reduce cognitive load, whereas children with high inhibitory control seem to be able to estimate time in parallel to solving arithmetical problem.

One of the limitations of this study is the small sample size, due to the use of an eye tracker, which necessitated a lab setting. The use of a participant volunteer database and testing in a lab setting also likely biased our recruitment towards children from higher socio-economic backgrounds, and with higher cognitive abilities. The next step would be to replicate our findings with a larger heterogeneous sample from online learning environments such as Math Garden to ensure the behavioural findings are reliable. Also, we chose a between-subjects design which minimises the effect of learning and testing time, but a within-subjects design would have had more power to detect interactions between the time pressure manipulation and individual differences in working memory and inhibitory control. Future work will investigate whether learning, rather than performance at a single timepoint, can be improved based on an adapted environment, informed by the results of the present study. Although the purpose of this study was to implement these findings in an online adaptive environment, the arithmetic problems used were standardised to ensure that we could compare arithmetic performance within this sample size. Due to our wide age range (8-11 years), certain arithmetic problems were inevitably less challenging for some children, therefore all analyses were covaried for age. Note however that there are large individual differences within year groups on arithmetic tasks (Straatemeier, 2014), so a more homogeneous sample in terms of age may have still shown considerable variability in arithmetic performance. To further investigate whether the associations between IC, WM, time pressure and arithmetical outcome change with age, the difficulty level of the arithmetic problems should be adapted to the ability of the child. Finally, while we considered the coin countdown to reflect time pressure, it also indicated the potential reward to be gained when correctly solving the problem. Although the reward obtained was shown to both groups of participants when a trial was completed, the group with no visible coin countdown did not have a constant reminder of the potential reward. This reward cue difference between the groups may have led to some of the differences observed between the conditions.

In conclusion, we found that the (in)visibility of time pressure, a key feature that is adaptable in a lot of online game-based learning environments and psychological tasks in general may create cognitive overload and impacts the application of knowledge and skills. Specifically, we show that this aspect of online game-based learning environments may differentially impact children’s arithmetic performance as a function of their cognitive abilities. Measuring the individual levels of cognitive functioning, in particular working memory and inhibitory control, is essential to allow children to perform and practise tasks at their highest level. In addition, the use of an eye tracker in this context allowed an in-depth exploration of how the learner interacted with the different elements in the environment above and beyond the accuracy and reaction time. Future work should focus on developing a broader online adaptive framework for learning mathematical skills and knowledge that adapts not only to a child's mathematical skills but also to their more general cognitive strengths and weaknesses.

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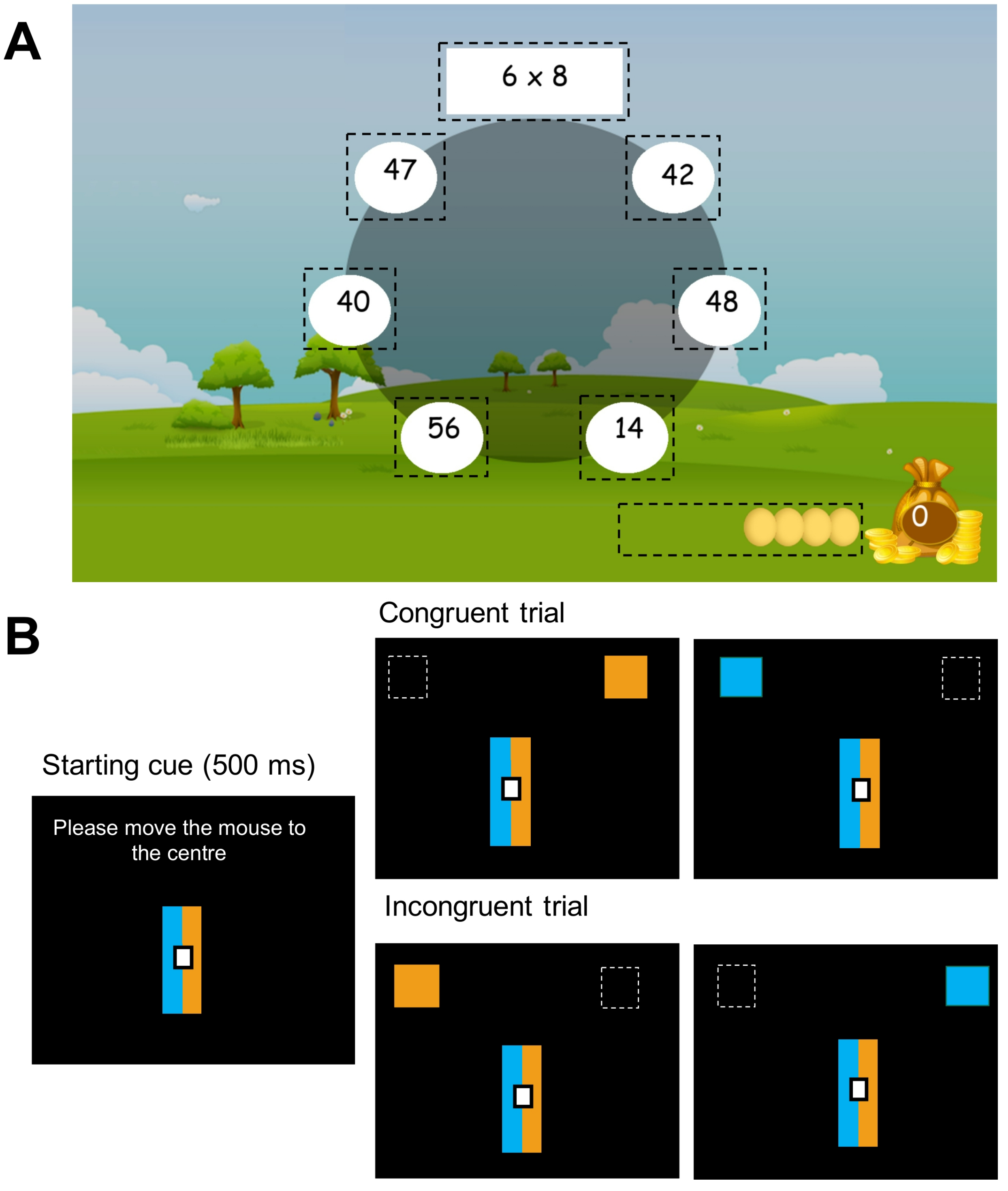
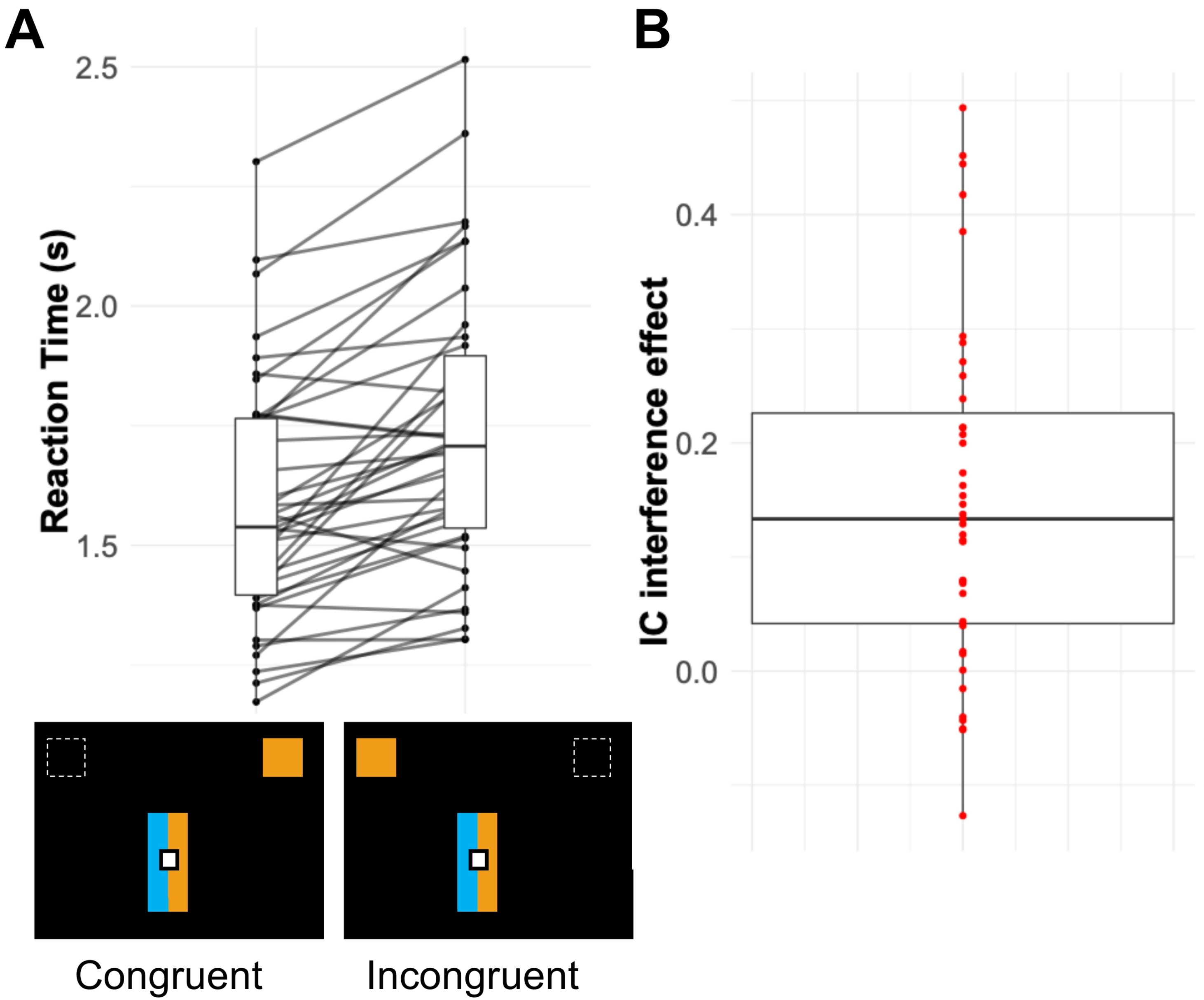
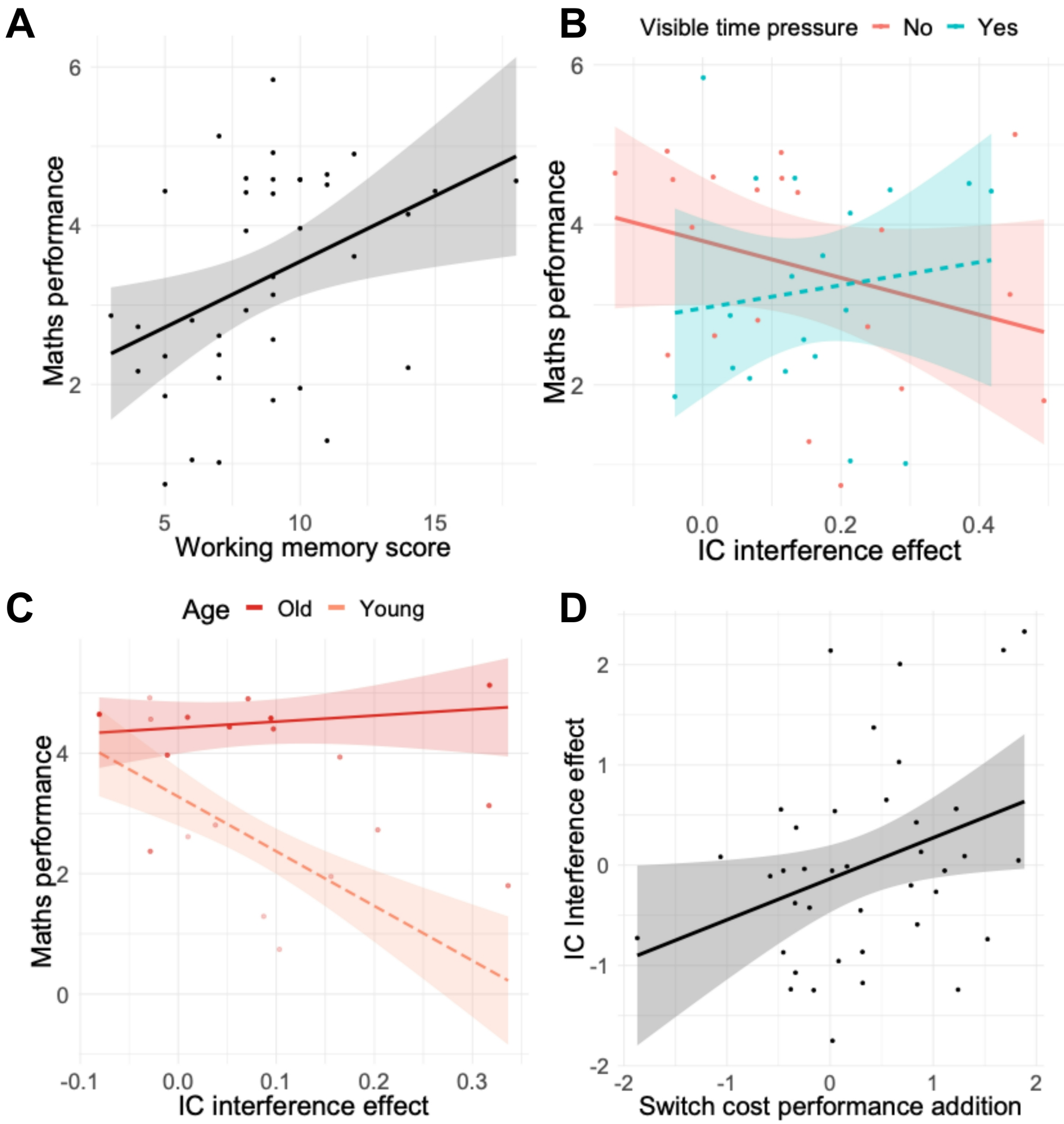
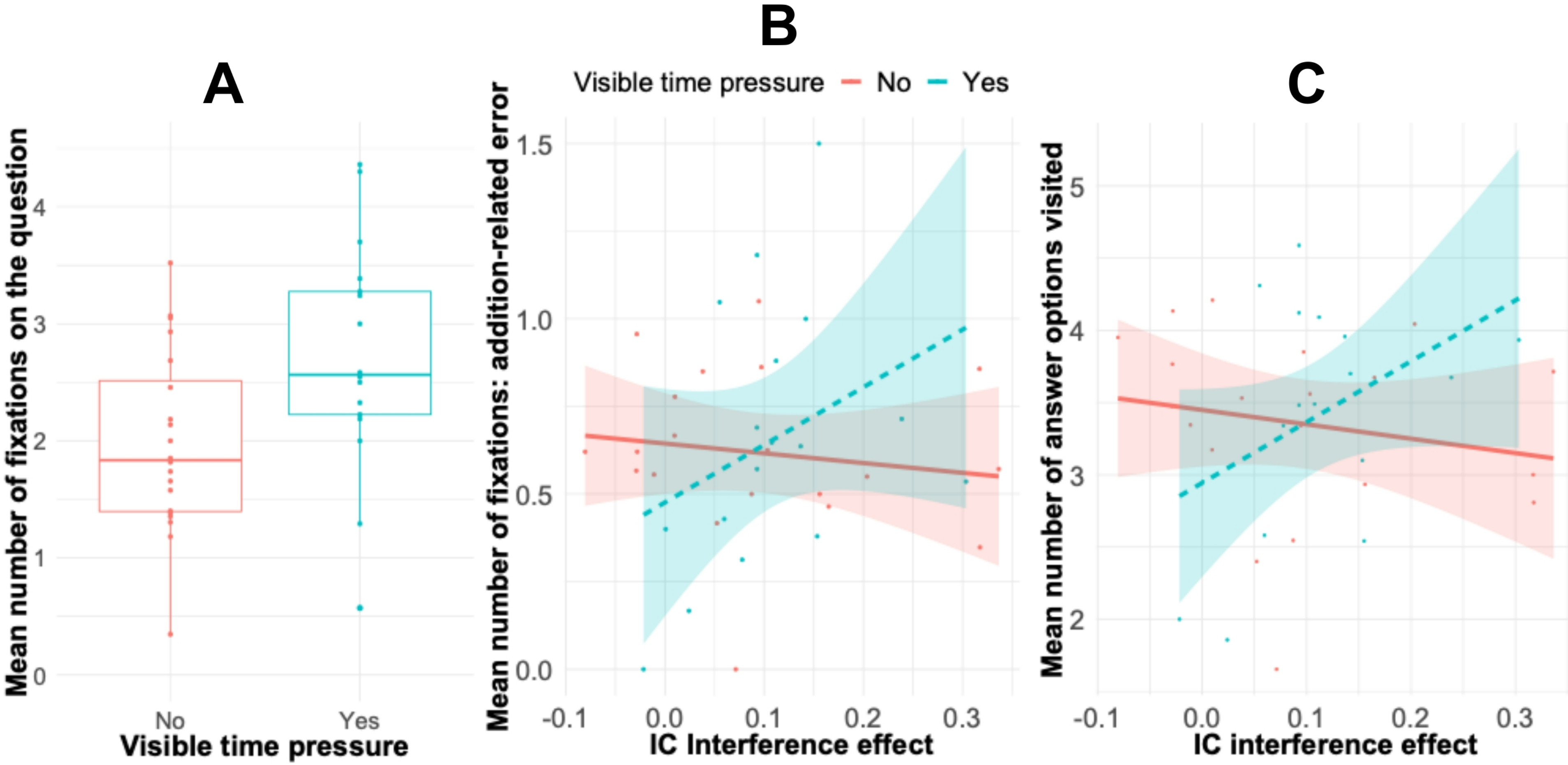


A
6 x 8
47
42
40
48
56
14
0
B
Congruent trial
Starting cue (500 ms)
Please move the mouse to the centre
Incongruent trial



A
B
2.5
2.0
1.5
Reaction Time (s)
0.4
0.2
0.0
IC interference effect
Congruent
Incongruent


A
Maths performance
Working memory score
B
Visible time pressure
No
Yes
Maths performance
IC interference effect
C
Age
Old
Young
Maths performance
IC interference effect
D
IC Interference effect
Switch cost performance addition



A
B
C
Visible time pressure
No
Yes
Mean number of fixations on the question
Mean number of fixations: addition-related error
IC Interference effect
Mean number of answer options visited
IC interference effect

Table 1 Comparison of the behavioural measures between the visible time pressure (TP) group and the no visible time pressure group. IC: inhibitory control; RT: reaction time; TOST: two one-sided equivalence test; WM: working memory

Variables	**Visible TP (*N* = 19)**	**No visible TP (*N* = 20)**	***TOSTs of equivalence***		
	Mean (*SD*)	**Mean (*SD*)**	***95% CI***		***p***
Age	9.46 (0.97)	9.73 (1.08)	-0.28	0.82	0.020
Prop. female	0.58	0.40	-0.09	0.45	<0.001
WM digit score	8.68 (3.42)	8.75 (3.08)	-0.53	0.57	0.002
IC interference effect	0.10 (0.08)	0.09 (0.12)	-0.63	0.46	0.004
RT maths task	4.08 (0.88)	3.85 (0.94)			
Prop. correct maths task	0.81 (0.16)	0.83 (0.17)			
Prop. no response maths	0.09 (0.08)	0.08 (0.11)			
Maths score	3.19 (1.34)	3.48 (1.35)			

Table 2: Summary of the effects observed in the ANCOVAs of the behavioural and eye tracking data. Effect sizes of significant effects (*p*'s < .05) are reported. Cases were robust support (BF > 3) for the alternative or the null hypothesis was provided by the Bayesian ANCOVAs are indicated with a [B.] Hyphens indicate the main effect or interaction was not significant but there was no strong evidence in support of the null hypothesis. TP = time pressure; WM = working memory; IC = inhibitory control.

Verbal working memory	**Age**	**TP**	**WM**	**Age x TP**	**WM x TP**	**WM x TP x Age**
1. Behavioural data[a]						
Maths performance	$\eta_p^2 = 0.53^B$	$null^B$	$\eta_p^2 = 0.24^B$	$null^B$	$null^B$	$null^B$
2. Eye tracking data (number of fixations) [b]						
Question box	-	$\eta_p^2 = 0.15^B$	-	-	-	-
Answer options	$null^B$	$null^B$	$null^B$	$null^B$	$null^B$	$null^B$

Inhibitory control	**Age**	**TP**	**IC**	**Age x TP**	**IC x TP**	**IC x TP x Age**
1. Behavioural data[a]						
Maths performance	$\eta_p^2 = 0.53^B$	$null^B$	$null^B$	$null^B$	$\eta_p^2 = 0.18^B$	$\eta_p^2 = 0.13^B$
Operation switch cost on multiplication problems	$null^B$	$null^B$	$null^B$	$null^B$	$null^B$	$null^B$
Operation switch cost on addition problems	-	-	$\eta_p^2 = 0.13$	-	-	$null^B$
2. Eye tracking data (number of fixations) [b]						
Question box	-	$\eta_p^2 = 0.15^B$	-	-	-	-
Operation errors on multiplication problems	-	$null^B$	-	-	$\eta_p^2 = 0.16^B$	-
Operation errors on addition problems	-	$null^B$	-	-	-	-
Answer options	-	-	-	-	$\eta_p^2 = 0.13$	-

[a] df = 31, [b] df = 28