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Learning-based before intentional cognitive control:

Developmental evidence for a dissociation between implicit and explicit control

Corentin Gonthier

University of Rennes

Solène Ambrosi & Agnès Blaye

University of Aix-Marseille

Corentin Gonthier, LP3C (EA 1285), University of Rennes, Rennes, France

Solène Ambrosi, Laboratoire de Psychologie Cognitive, LPC (UMR CNRS 7290), Aix  
Marseille Université, 13331 Marseille, France

Agnès Blaye, Laboratoire de Psychologie Cognitive, LPC (UMR CNRS 7290), Aix Marseille  
Université, 13331 Marseille, France

Correspondence concerning this article should be addressed to Corentin Gonthier,  
Laboratoire LP3C, Campus Villejean, Place du Recteur Henri Le Moal, CS 24307, 35043  
Rennes Cedex, France. E-mail: [corentin.gonthier@univ-rennes2.fr](mailto:corentin.gonthier@univ-rennes2.fr)

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### **Abstract**

Cognitive control can be triggered by explicit or implicit events; it has been proposed that these two possibilities tap into dissociable mechanisms. In this study, we investigate this idea by testing whether young children, who struggle with explicitly-triggered control, can demonstrate proportion congruency effects - which are based on implicit learning of task regularities and thus indicative of implicitly-triggered control. In a series of five experiments, preschoolers indeed demonstrated significant proportion congruency effects, including both list-wide proportion congruency (LWPC) and item-specific proportion congruency (ISPC) effects, in a Stroop-like task and in a flanker task. These effects did not increase with age, contrary to what is typically observed for explicit control. These results demonstrate that young children show early evidence of cognitive control - including proactive control - when it is triggered by implicit events, at an age where explicit control, and particularly proactive control, is not yet functional. By showing evidence of an early ability for fine-grained adjustments of cognitive control when control cues are learned implicitly, these results support the proposed functional dissociation between explicit and implicit cognitive control.

### **Keywords**

Implicit cognitive control; Proportion congruency effects; List-wide proportion congruency (LWPC); Item-specific proportion congruency (ISPC); Proactive control

How do you know when it is time to control your behavior? Cognitive control is the ability to regulate behavior so as to produce a goal-directed response, in a situation that cannot be resolved automatically (Miller & Cohen, 2001): by definition, it must be triggered by something (Botvinick et al., 2001). Two major possibilities have prompted considerable debate in the cognitive control literature: control may be triggered based on explicit events or based on implicit events (hereafter explicit and implicit control; Blais, 2010; Bugg et al., 2015; Kunde et al., 2012; see also van Gaal et al., 2012). In this paper, we investigate the distinction between explicit and implicit cognitive control by considering the possibility that the two develop differently.

### **Developmental Evidence as a Window into Explicit and Implicit Control**

Cognitive control can be viewed as explicit when it is based on a cue that explicitly signals what is required of the subject: for example, a prompt to refrain from responding to an impending stimulus. In this case, cognitive control may be implemented in a top-down fashion, as guided by the subject's expectations (Bugg et al., 2015). This form of control is usually thought to be performed intentionally, and with awareness, although this is not a necessity (Blais, 2010; Bugg et al., 2015; Hommel, 2007, 2013; Kunde et al., 2012). By contrast, cognitive control can be viewed as implicit when it is based on information learned incidentally from the task: for example, the experience that conflict occurs frequently in the task, requiring heightened cognitive control. This form of control is implemented in a bottom-up fashion, with control settings being adjusted as a function of learned experience in the task (Botvinick et al., 2001, 2004; Verguts & Notebaert, 2008), presumably without awareness (Blais, 2010; Blais et al., 2012; Crump et al., 2006, 2008; Kunde et al., 2012).

The relative contributions of explicit and implicit triggers to cognitive control have been frequently debated, sometimes under other headings (such as whether control is conscious or unconscious, intentional or automatic, endogenous or exogenous; e.g. Hommel,

2007, 2013). It has recently been proposed that the two may in fact represent dissociable mechanisms, which may come with different constraints and which may reflect meaningfully different processes (Bugg et al., 2015; Bugg & Crump, 2012; Cohen-Shikora et al., 2018; Kunde et al., 2012). For example, explicit cues may allow one to relax but not heighten control in a particular situation (Bugg et al., 2015); implicit control may require conscious awareness of the events subtending implicit learning, whereas explicit cognitive control may be triggered based on subliminal events (Kunde et al., 2012). One way to test whether explicit and implicit cognitive control are indeed dissociable mechanisms is to use paradigms involving both explicit and implicit manipulations, and to assess their respective effects on performance (e.g. Bugg et al., 2015; Entel et al., 2014). Another possibility is to study populations where the two mechanisms may not be equally functional: nonhuman primates (Washburn, 2016), older adults (Bugg, 2014a; Cohen-Shikora et al., 2018), or children.

Preschoolers have well-known difficulties in engaging cognitive control based on explicit cues (Chevalier, 2015a, 2015b; Davidson et al., 2006; Diamond, 2013; Huizinga et al., 2006; Macdonald et al., 2014; Munakata et al., 2012; Zanolie & Crone, 2018; Zelazo et al., 2013). Note that there is no abrupt transition such that preschoolers fail and older children succeed at explicit cognitive control tasks: on the contrary, the literature has shown that improvements continue until late adolescence. For example, one of the most widely used tasks to measure explicit control in young children, the dimensional change card sort or DCCS, shows that children younger than 5 years old particularly struggle with the task; but performance steadily increases up to at least 15 years old (see Zelazo et al., 2013).

Studies focused more precisely on mechanisms of control have illustrated a number of difficulties of preschoolers in explicit cognitive control. For example, preschoolers are less skilled than older children at focusing their attention on explicit cues (Chevalier et al., 2010, 2018; Karbach & Kray, 2007) and identifying the goal to pursue (for a review, see Chevalier,

2015a). Preschoolers benefit more than older, school-age children, from transparent goal cues in cognitive control tasks (Chevalier & Blaye, 2009; Blaye & Chevalier, 2011) and from labelling the relevant information before responding (Müller et al., 2004), pointing to a difficulty in converting explicit cues into goals or actions. The ability to maintain and implement explicit task goals experiences a drastic increase throughout childhood (Korbach & Kray, 2007; Chevalier & Blaye, 2008, 2009; Chevalier et al., 2010, 2012, Morton & Munakata, 2002; Munakata et al., 2012, 2014). Preschoolers are prone to neglecting the task goal (Bub et al., 2006; Diamond & Taylor, 1996; Towse et al., 2007; Zelazo et al., 2003), and benefit more than older children from the experimenter's verbal reminding of the goal (Barker & Munakata, 2015). Likewise, developmental improvements in cued task-switching are often attributed to improvement in goal setting rather than in implementing a switch per se (e.g., Cepeda et al., 2001; Chevalier & Blaye, 2009; Chevalier et al., 2010; Korbach & Kray, 2007; Lucenet et al., 2014; Reimers & Maylor, 2005).

A specific difficulty of young children is explicit proactive control - that is, engaging cognitive control in advance, before the critical event occurs, based on explicit predictive cues (for details on proactive control, see Braver et al., 2007). In fact, preschoolers seem to rely first and foremost on reactive control, waiting for the event requiring control to occur (Chatham et al., 2009; Chevalier, James, et al., 2014; Lucenet & Blaye, 2014; Munakata et al., 2012). The transition towards explicit proactive control occurs around 5-6 years old (Gonthier et al., 2019), but continuing increases in the use of proactive control are observed into early adulthood (Lorsbach & Reimer, 2008, 2010; Polizzotto, 2018). Preparatory prefrontal activation during the delay following explicit task cues also appears to be underdeveloped in childhood (Church et al., 2017). This has prompted several authors to state that young children do not explicitly use proactive control, and rely on reactive control instead (e.g. Barker & Munakata, 2015; Chevalier, 2015b; Munakata et al., 2012).

This established difficulty for young children (around 5 years old) to engage in cognitive control based on explicit events, and particularly in explicit proactive control, offers an opportunity to explore the role of implicit learning and the difference between explicit and implicit control. If preschoolers who struggle with control based on explicit cues nonetheless demonstrate cognitive control similar to adults when control settings are learned from implicit cues, this will constitute evidence not only that implicit learning can play a central role in cognitive control, but also that there may be a meaningful functional dissociation between explicit and implicit cognitive control (for a similar point with older adults, see Cohen-Shikora et al., 2018).

### **Implicit Cognitive Control and its Development in Children**

Implicit cognitive control has been described using the conflict monitoring framework proposed by Botvinick and colleagues (2001, 2004). This account views conflict as central to human information processing (see Botvinick et al., 2001) and as a naturally aversive state (Botvinick, 2007; Dreisbach & Fischer, 2015), which should be easily detected by children as well as adults. According to this framework, the ongoing task is continuously monitored for the occurrence of conflict in information processing - such as a competition between two possible responses. This continuous conflict monitoring is subtended by the anterior cingulate cortex. Detection of conflict signals a demand for increased cognitive control, as implemented by the prefrontal cortex (Botvinick et al., 2001, 2004; see also Braver et al., 2007; Miller & Cohen, 2001). As conflict is repeatedly detected in a task, the likelihood of conflict for a given item or context can be learned through a form of associative learning (Verguts & Notebaert, 2008), allowing for dynamic adjustments of control implementation on subsequent stimuli.

This process of conflict monitoring, learning and adjustments of cognitive control can take place over short timescales: within one or several trials. In this case, it is notably

reflected in sequential congruency effects (decreased interference after a conflicting trial) and in post-error slowing (see Botvinick et al., 2001). Both effects have been found in young children: (1) sequential congruency effects have been observed in children from 5 years onwards (Ambrosi et al., 2016; Iani et al., 2014; for studies in older children, see also Larson et al., 2012; Wilk & Morton, 2012), although the results are not always clear-cut (Waxer & Morton, 2011); and (2) post-error slowing effects have been observed by the age of 4 years (Gupta et al., 2009; McDermott et al., 2007; Wiersema et al., 2007). This suggests that the basic mechanisms required to engage cognitive control based on implicit cues can be functional in preschoolers (if not earlier).

Critically, conflict monitoring and control adjustments can also take place over longer timescales on the order of minutes, encompassing a whole task block (Botvinick et al., 2001; De Pisapia & Braver, 2006): in essence, participants can implicitly learn the likelihood of conflict in a given context and adjust control accordingly. This situation is reflected in proportion congruency (PC) effects, wherein interference is reduced when most trials are conflicting. Where post-error slowing and sequential congruency effects reflect very local adjustments of control as a function of the immediately preceding trial, PC effects are conceptually more complex in that they reflect more general adjustments depending on the overall amount of experienced conflict, as learned across a series of trials.

Contrary to post-error slowing and sequential congruency effects, little is known about PC effects in children. Two studies have shown that preschoolers make fewer errors following new task rules when old and new rules conflict on a high proportion of trials, a conceptually close analogue to PC effects (Marcovitch et al., 2007, 2010). A couple of studies have also revealed PC effects in children from 9 years onwards, with no change up to adulthood (Surrey et al., 2019; Wilk and Morton, 2012), leaving untouched the question of earlier ability. In this study, we focus on whether preschoolers can demonstrate PC effects.



### **Proportion Congruency Effects as an index of Implicit Control**

Proportion congruency effects are typically studied in conflict tasks; a classic example is the Stroop task, in which participants respond to the ink color of a written color name, while refraining from the prepotent response of reading the word itself (Stroop, 1935). The task can include congruent trials, where the printed color matches the word, and incongruent trials, when the two pieces of information conflict. Incongruent trials elicit conflict, which requires cognitive control to be resolved, yielding slower RTs and higher error rates. Critically, the proportion of congruent and incongruent trials in the task has been shown to lead to a modulation of cognitive control (e.g. Tzelgov et al., 1992). When conflict is frequent, participants tend to demonstrate less interference: in other words, there is less difference between performance on congruent and incongruent trials, reflecting reduced reliance on the irrelevant process of word reading.

The adult literature has distinguished at least two types of PC effects: list-wide (LWPC) and item-specific (ISPC). For the LWPC effect, PC is manipulated at the level of an entire task block: the list of trials is mostly congruent (MC) or mostly incongruent (MI). Interference is smaller in a MI block than in the MC block. The usual interpretation is that subjects implement a proactive or global form of control in the MI block: learning that conflict is more likely in this block, and biasing attention away from word reading throughout all trials (e.g. Gonthier, Braver, et al., 2016; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). For the ISPC effect, PC is manipulated at the level of items: some items within a task block are MC (for example, the word *red* could be usually written with red ink) and other items are MI (for example, the word *yellow* could be usually written with ink that is not yellow). Interference is smaller for MI items than for MC items (Jacoby et al., 2003). This is interpreted as subjects implementing an item-specific or reactive form of control: learning that the likelihood of conflict is greater for a particular set of items, and

selectively engaging cognitive control when these items are presented (e.g. Gonthier, Braver, et al., 2016; see also Bugg & Hutchison, 2013; Bugg et al., 2011; Bugg et al., 2008).

If implicit cognitive control is functionally similar to explicit control, then it is doubtful that either type of PC effect could be observed in preschoolers, albeit for partly different reasons. ISPC effects are taken to reflect reactive control, which is operative in young children (Chevalier et al., 2018; Gonthier et al., 2019); but they also require considerable flexibility to adjust control settings on-the-fly after each specific item is presented, and preschoolers have major difficulties with explicitly switching from a task or a mental set to another (e.g. Cepeda et al., 2001; Espy & Cwik, 2004; Jacques & Zelazo, 2001; Reimers & Maylor, 2005), difficulties which could translate to the implicit form of reactive control represented by ISPC effects. As for LWPC effects, these appear to reflect proactive control (global, anticipatory), and the current consensus in the literature is that preschoolers do not spontaneously use explicit proactive control (Chatham et al., 2009; Chevalier et al., 2014; Gonthier et al., 2019; Lucenet & Blaye, 2014; Munakata et al., 2012), so they should not demonstrate the implicit form of proactive control represented by LWPC effects either. If implicit and explicit control are functionally similar, we would therefore predict LWPC effects and possibly ISPC effects to be absent in preschoolers or, at the very least, to demonstrate considerable increases within the 5-6 years old to 8-10 years old timeframe where major changes in explicit cognitive control take place (Chevalier, 2015b; Munakata et al., 2012).

On the other hand, if implicit control is meaningfully distinct from explicit control, it seems plausible that PC effects could be observed in preschoolers. The basic mechanisms for conflict detection and the corresponding adjustments of control seem to be functional in early childhood, given the existence of sequential congruency and post-error slowing effects. PC effects also require implicit learning of environmental regularities (how likely is conflict to

occur for a given set of items or a given task block?); many studies have shown that such implicit statistical learning is operative in infants aged of a few months, and is relatively invariant throughout development (Amso & Davidow, 2012; Aslin & Newport, 2012; Saffran et al., 1996). Furthermore, implicit learning of the regularity of conflict in a given task seems to occur easily even in older adults, in as few as six trials (Cohen-Shikora et al., 2018), and PC effects are even found in nonhuman primates (Washburn, 2016).

If explicit and implicit control differ, it could even be the case that LWPC effects could be observed in young children, given that the inability of preschoolers to use proactive control has always been observed using experimental paradigms where proactive control was to be triggered by explicit events. This is especially true of the AX-CPT paradigm (see Braver et al., 2019; Gonthier et al., 2019): while not outright described as an "explicit proactive control" task in the literature, this paradigm requires a response to a probe letter based on a cue letter presented explicitly, and requires explicit response preparation (e.g. when the cue letter is not an A, the probe letter will always require a "nontarget" response, which subjects can prepare in advance). This explicit nature is reflected in experimental manipulations used to induce proactive control, where subjects are explicitly asked to prepare their response after the cue, for example by repeating out loud "non-target, non-target, non-target" when the cue is not an A (see Braver et al., 2009; Edwards et al., 2010; Gonthier, Macnamara, et al., 2016; Paxton et al., 2006). Yet despite being often measured with this type of task, at its core proactive control is defined by its temporality, not by being intentional: it could be based on implicit learning (De Pisapia & Braver, 2006) and the LWPC effect can thus be viewed as an implicit form of proactive control (Bugg et al., 2015; Cohen-Shikora et al., 2018; Gonthier et al., 2016). This makes the LWPC effect particularly relevant to our purposes: preschoolers should demonstrate a LWPC effect if and only if there is a meaningful functional distinction between explicit and implicit (proactive) control.

## **Rationale for the Present Study**

The current study was designed to determine whether PC effects exist in preschool children, and whether they increase throughout development. Our objective was to investigate PC effects as a window into implicit cognitive control, with a focus on LWPC effects as a form of implicit proactive control, and ISPC effects as a form of implicit reactive control.

We believed this question to be doubly interesting. (1) From the point of view of cognitive control in general, this was a way to investigate the proposed dissociation between explicit and implicit control, in a population other than young adults who can use both mechanisms effectively. If children too young to effectively use cognitive control based on explicit cues nonetheless demonstrated PC effects similar to older children, this would confirm both that cognitive control can be robustly implemented based on relatively low-level implicit learning, and that this form of implicit control can be functionally different from explicit control. Finding evidence of LWPC effects in particular would be especially interesting, in showing that proactive control can be engaged through implicit learning of conflict likelihood, even in subjects who have been shown to have difficulty initiating this mode of control intentionally. (2) From a developmental standpoint, this was also a way to determine whether young children have in fact more cognitive control skills than previously thought, at least when cognitive control is recruited implicitly based on learning environmental regularities, rather than engaged intentionally by the child.

To investigate these questions, our experiments included 5-6 years old children, who have well-known difficulties engaging in cognitive control based on explicit cues, and in explicit proactive control in particular (Gonthier et al., 2019). The first aspect of our study was to test whether ISPC and especially LWPC effects could be observed at all in this age group. As a point of reference, we also included 8-10 years old children, an age category in

which PC effects seem comparable to adult levels (Surrey et al., 2019; Wilk and Morton, 2012). The second aspect of our study was to test whether ISPC and LWPC effects increased from 5-6 years old to 8-10 years old. If implicit and explicit control relied on functionally identical mechanisms, we expected to find small or null PC effects in the 5-6 years old group and larger effects in the 8-10 years old group; if the two forms of control were dissociable, we expected to find PC effects in the 5-6 years old group, similar in size to the 8-10 years old group (or even larger in the younger group due to baseline differences in response speed; see Smulders et al., 2018).

Experiment 1 constituted a starting point to test whether PC effects existed at all in children, and thus whether the basic process of learning conflict likelihood and adjusting cognitive control accordingly was functional even at an early age. To this end, we used a variant of the Stroop task with a simple design including biased items within biased task blocks, confounding LWPC and ISPC effects. The next series of experiments served to disentangle the contribution of proactive and reactive control mechanisms, with Experiments 2a and 2b testing LWPC effects for unbiased items within biased task blocks, and Experiments 3a and 3b testing ISPC effects for biased items within unbiased task blocks. Because part of the objective was to test whether children can differentially implement cognitive control based on learning environmental regularities, PC was manipulated within-subjects in all experiments.

As a way to generalize our findings, Experiments 1, 2a and 3a used a Stroop-like task, whereas Experiments 2b and 3b used a flanker task. To help ensure that control implementation was truly implicit, Experiments 2b and 3b also tested awareness of the PC manipulations (similar to Blais et al., 2010; Crump et al., 2008). Experiments were designed to ensure, as much as possible, that PC effects were driven by cognitive control rather than alternative mechanisms such as contingency learning (for a review, see Braem et al., 2019):

in particular, item sets were indexed by the relevant dimension in the task, there were always four possible responses to a given item, and analyses were performed on trials with no overlap between item sets (Bugg & Gonthier, 2020).

As another way to ensure the contribution of cognitive control, we also tested for the asymmetrical list shifting effect (Abrahamse et al., 2013; see also Kane & Engle, 2003) in the three experiments where PC effects were manipulated at the level of a task block (Experiments 1, 2a and 2b). The asymmetrical list shifting effect occurs if the difference of interference between MC and MI conditions is smaller when the MI block is performed before the MC block, than when the MC block is performed before the MI block. This pattern indicates that subjects have implicitly learned cognitive control settings in the MI block and then transferred them to the MC block (whereas alternative mechanisms such as contingency learning should be relatively invariant to task order; see Abrahamse et al., 2013).

### **Experiment 1: Proportion Congruency Effects in the Stroop Task**

The first objective of Experiment 1 was to test whether preschoolers demonstrate a PC effect at all. We investigated this possibility in a group of 5-6 years old children, with a group of 8-9 year-olds included as a point of reference to test whether the magnitude of PC effects increases during childhood. To maximize our chances of observing a PC effect in young children, we used a simple design: task blocks had a high degree of bias (83% congruent or incongruent), and all stimuli within a block were equally biased (confounding LWPC and ISPC manipulations).

Testing PC effects required a conflict task, but most available conflict tasks were unsuitable for this purpose: the word reading required by the classic Stroop task was not appropriate for 5-6-year-olds, and child-friendly variants such as the day-night Stroop (Montgomery & Koeltzow, 2010) typically include only two items, which can involve

mechanisms other than cognitive control such as contingency learning (see Braem et al., 2019; Schmidt & Besner, 2008). We chose to use the fruit Stroop (Archibald & Kerns, 1999; see also Ambrosi, Lemaire, & Blaye, 2016; Macdonald et al., 2015; Okuzumi et al., 2014), where children view fruits colored in correct (e.g. a banana in yellow) or incorrect colors (e.g. a banana in red), and answer according to the canonical color of the fruit rather than its displayed color (for example, children should always answer "yellow" for a banana regardless of whether it is displayed in yellow or in another color). This task requires no word reading and allows for four stimuli, while resembling the classic Stroop in its use of matching and mismatched colors. The fruit Stroop does differ from the classic Stroop in the sense that it requires retrieval of a stimulus feature in long-term memory (as do other variants of the Stroop, e.g. Konkle & Oliva, 2012), but it retains the core structure of responding to a relevant dimension, while disregarding a prepotent but irrelevant dimension (the displayed color, which encourages pressing the response key of the same color through simple perceptual matching), and provides results similar to the classic Stroop (for a discussion, see Prevor & Diamond, 2005; see also Okuzumi et al., 2015).

A secondary objective was to ensure that the PC effect was attributable to actual cognitive control, rather than to other mechanisms. To test for the asymmetrical list shifting effect (Abrahamse et al., 2013), Experiment 1 included two order conditions for the MI and MC task blocks (MC followed by MI or MI followed by MC). Another alternative explanation for a PC effect would be practice effects, wherein interference would be reduced in the second block regardless of its proportion congruency; indeed, practice with a task can sometimes improve performance in a way that closely resembles the pattern observed when participants engage in sustained cognitive control (for an example, see Paxton et al., 2006; see also Spinelli & Lupker, 2020). To control for this possibility, we included a third condition where children completed two consecutive 50% congruent blocks. This made it

possible to ensure that the difference observed between MC and MI blocks was greater than the difference observed due to practice on two consecutive 50% blocks.

## **Method**

### ***Sample Size***

Given the lack of similar studies in the literature, we had no way of estimating the effect size of the possible interaction between age and PC effects. In this and the following experiments, data collection was therefore planned to optimize the chances of finding a PC effect in the younger age group. Studies on mixed PC effects (confounding LWPC and ISPC manipulations) with adults have typically found robust effects with small samples sizes (e.g. between 8 and 32 subjects for Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). Another objective of this experiment was to test for an asymmetrical list shifting effect, which was obtained in adults with similar sample sizes (e.g. Abrahamse et al., 2013, recruited 42 subjects and found  $\eta^2_p = .32$ ). Given the uncertainty regarding whether these effects could be observed in children, we decided to collect double this sample size in each group. We thus planned data collection for four classes per age group (about 100 children per group, or 200 children total), so as to retain about 33 children per age group per condition (i.e. about 66 subjects in the MI-MC and MC-MI conditions testing for the PC effect). All children in a class were invited to complete the experiment, so that the final sample size within an age group depended of the number of children for whom consent could be obtained in the planned number of classes.

### ***Participants***

A sample of 173 children participated in the study. This sample comprised 91 children in kindergarten (50 females and 41 males; mean age = 5.75 years, range = 5.42 to 6.33 years) and 82 children in 3<sup>rd</sup> grade (37 females and 45 males; mean age = 8.92 years, range = 8.42 to



9.42 years). Participating children were recruited in French public schools and had never participated in an experiment before. They were predominantly White and of average socioeconomic status, reflecting the characteristics of the local community. All participants spoke French as their first language and attended the class corresponding to their age group. Experimental conditions were counterbalanced within each class. Informed written consent was obtained from the children's parents and all children provided verbal assent to participate. The approval of an ethics committee was not required under local regulations.

### ***Materials***

The Stroop task (adapted from Archibald & Kerns, 1999 and Ambrosi, Lemaire, & Blaye, 2016) was programmed in E-Prime (Psychology Software Tools, Pittsburgh, PA; version 2.10) and presented on a laptop with a 15-inches screen. Each trial began with a fixation cross (+) displayed for 850 ms in the center of the screen, followed by the stimulus which remained on the screen until response (see Figure 1a)<sup>1</sup>. Stimuli were line drawings (250 x 250 pixels) of a strawberry, a banana, a salad, or a carrot presented in the center of the screen. On congruent trials the drawings were displayed in their canonical color (i.e., strawberry in red, banana in yellow, carrot in orange, salad in green). On incongruent trials they were presented in one of the three other non-usual colors (e.g., strawberry in yellow, orange or green). Children were instructed to press the key corresponding to the canonical color of the stimuli (*s* for red, *d* for yellow, *k* for orange, *l* for green). Each key was signaled by a colored sticker, thereby alleviating potential memory load.

[Insert Figure 1 approximately here]

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<sup>1</sup> In adult conflict tasks, stimuli are sometimes displayed for a limited duration (though not always; e.g. Bugg & Gonthier, 2020; Gonthier et al., 2016). In young children, it is critical that the task remains subject-paced: both because children of different ages have very different response speeds and an appropriate duration for one group would not be appropriate for the other, and because this makes it possible to momentarily pause the task if the child loses focus or needs to be reminded of the instructions.

### *Design*

Children performed either a MC block followed by a MI block, a MI block followed by a MC block, or two 50% congruent blocks; hereafter MC-MI, MI-MC and 50-50 conditions. Each block comprised 100 trials, with three breaks. The first trial and the first trial occurring after each break were discarded, leaving 96 critical trials per block. The MC block included 83% of congruent trials: each of the four fruits was displayed 20 times in its canonical color (e.g., a carrot colored in orange) and 4 times in a non-usual color (e.g., a carrot colored in green). The MI block involved 83% of incongruent trials: each of the four fruits was displayed 4 times in their canonical color and 20 times in a non-usual color<sup>2</sup>. The 50% block included 50% of congruent trials: each of the four fruits was displayed 12 times in its canonical color and 4 times in each of the three non-usual colors. This design is summarized in Table 1. Trials within a block were presented in the same pseudorandom order for all participants; neither the displayed fruit, nor the color were repeated across two consecutive trials.

[Insert Table 1 approximately here]

### *Procedure*

Children were tested individually in a quiet room at their school. The experiment included a familiarization phase, allowing the experimenter to ensure that all children knew the color names, the fruit names and their canonical colors. First, there were 8 trials requiring children to respond to the four colors (represented as splashes of colors) by pressing the

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<sup>2</sup> Note that the design was not perfectly balanced for MC and MI blocks (e.g. bananas in the MC block appeared twice in red but only once in orange and green): there was no straightforward solution to make all possible combinations of fruits and colors occur equally often while at the same time limiting the total number of trials and keeping a high degree of bias in the MC and MI blocks. However, at the block level, each fruit appeared equally often (24 times), thus equating the probability of each response (red, yellow, orange, and green) to be correct; each color was also presented equally often (24 times) and counterbalanced across fruits.

corresponding key. Then there were 8 trials where children had to indicate the canonical colors of the fruit drawings, presented in black and white. Lastly, there was a practice phase of 16 trials (corresponding to all possible combinations of fruits and colors), in the same conditions as the main task. After completing the practice trials, children received the two series of test trials corresponding to their experimental group, for a total of 200 trials. They were instructed to respond as quickly as possible without making errors. The whole procedure lasted approximately 20 to 30 minutes.

Children were randomly assigned to one of the three experimental groups : 31 kindergarteners and 26 third-graders performed a MC block followed by a MI block, 26 kindergarteners and 29 third-graders performed a MI block followed by a MC block, and 30 kindergarteners and 26 third-graders performed two consecutive 50% congruent blocks. Children were never informed of the proportion of compatible trials they would encounter.

### ***Data Processing***

Response times were analyzed for trials with a correct answer only. We used the same exclusion criteria as in a prior study (Gonthier, Braver, et al., 2016): trials with a RT faster than 200ms or slower than 3000ms were dropped from the analyses, and children with a Stroop effect more than three standard deviations from the average of their age group were excluded from the sample. We also excluded children with error rates of at least 50% on any trial type. The data for this and other experiments are available on [osf.io/mrqek/](https://osf.io/mrqek/) (Gonthier, Ambrosi, & Blaye, 2020).

### **Results**

Two children in the 5-6 years old group (with error rates above 50% on incongruent trials) were excluded, yielding a final sample size of  $N = 171$  ( $n = 89$  in the 5-6 years old

group and  $n = 82$  in the 8-9 years old group). Descriptive statistics for all measures are displayed in Table 2.

[Insert Table 2 approximately here]

### *Existence of a Proportion Congruency Effect, as a function of Age*

The first series of analyses investigated whether a PC effect could be found, and whether this effect varied as a function of age. This analysis was restricted to subjects who performed the MI and MC blocks (collapsing across the MC-MI and MI-MC conditions, excluding subjects in the PC-50 condition), with a sample size of  $n = 113$  ( $n = 58$  in the 5-6 years old group,  $n = 55$  in the 8-9 years old group). Statistical analyses were performed using mixed-design ANOVAs, including proportion congruency (MC vs. MI) and trial type (congruent vs. incongruent) as within-subjects variables and age group (5-6 years old vs. 8-9 years old) as a between-subjects variable.

For RTs, there was a main effect of trial type,  $F(1, 111) = 271.08$ ,  $p < .001$ ,  $\eta^2_p = .71$ , reflecting slower RTs for incongruent trials. This effect interacted with list-wide PC,  $F(1, 111) = 31.48$ ,  $p < .001$ ,  $\eta^2_p = .22$ , indicating that interference was reduced in the MI condition when compared to the MC condition (PC effect). This interaction is displayed in Figure 2a. The main effect of age was significant,  $F(1, 111) = 136.72$ ,  $p < .001$ ,  $\eta^2_p = .55$ , indicating faster response times for older children; however, the three-way interaction between age, PC and trial type was non-significant, suggesting that the magnitude of the PC effect did not differ as a function of age,  $F(1, 111) = 1.52$ ,  $p = .220$ ,  $\eta^2_p = .00$ . Analyzing the same three-way interaction for log-transformed RTs (which expresses interference in proportionate terms, as a ratio between congruent and incongruent RTs, so as to take age differences in baseline response speed into account; e.g. Kliegl et al., 1994; Meiran, 1996)

confirmed that the PC effect was not substantially different for the two age groups,  $F(1, 111) = 0.10, p = .708, \eta^2_p = .00$ .

For error rates, there was a main effect of trial type, indicating a higher error rate on incongruent trials,  $F(1, 111) = 161.16, p < .001, \eta^2_p = .59$ . This effect interacted with list-wide PC,  $F(1, 111) = 22.43, p < .001, \eta^2_p = .17$ , again showing reduced interference in the MI condition when compared to the MC condition. This PC effect is represented in Figure 2b. The main effect of age was non-significant,  $F(1, 111) = 2.34, p = .129, \eta^2_p = .02$ , as was the three-way interaction between age, PC and trial type,  $F(1, 111) = 0.88, p = .350, \eta^2_p = .01$ , again indicating that the PC effect did not differ for the two age groups.

[Insert Figure 2 approximately here]

### ***Controlling the Effects of Practice and List Order***

This series of analyses included the whole sample, and was performed using a 3 (condition: MC-MI vs. MI-MC vs. 50-50) x 2 (task block: first block vs. second block) x 2 (trial type: congruent vs. incongruent) mixed-design ANOVA. To streamline the results, age was not included as a factor given the finding that it did not moderate the PC effect; results were similar when controlling for age and when analyzing data separately for the two age groups, and the effects of interest showed no significant interaction with age (all  $ps > .26$ ). The results are depicted in Figure 3a for RTs and in Figure 3b for error rates. Critically, the three-way interaction between experimental condition, task block and trial type was significant for both RTs,  $F(2, 168) = 21.30, p < .001, \eta^2_p = .20$ , and error rates,  $F(2, 168) = 15.54, p < .001, \eta^2_p = .16$ , indicating that the difference between lists varied as a function of experimental condition and could not be summarized as a practice effect. The next analyses decomposed these interactions.

We first examined the effect of task block order, restricting the analysis to the MI-MC and MC-MI conditions. For RTs, block order interacted with the PC effect,  $F(1, 111) = 5.86$ ,  $p = .017$ ,  $\eta^2_p = .05$ , in the predicted direction: the difference of interference between the MI and MC conditions was greater in the MC-MI condition (155 ms) than in the MI-MC condition (65 ms). A contrast analysis indicated that this interaction was driven by the MC condition, where interference was significantly smaller in the MI-MC condition than in the MC-MI condition,  $F(1, 111) = 10.86$ ,  $p = .001$ ,  $\eta^2_p = .09$  (see Figure 3a). For the MI condition, interference was similar in the MI-MC condition and the MC-MI condition,  $F(1, 111) = 0.36$ ,  $p = .549$ ,  $\eta^2_p = .00$ . A similar pattern appeared for error rates, where the PC effect also interacted with block order,  $F(1, 111) = 8.66$ ,  $p = .004$ ,  $\eta^2_p = .07$ , also in the predicted direction (see Figure 3b): the difference of error rates between the MI and MC conditions was greater in the MC-MI condition (.07) than in the MI-MC condition (.02).

Turning next to the effect of practice, the 50-50 condition was compared with the MC-MI and MI-MC conditions using a contrast analysis. The difference of interference between the first block and second block was significantly different between the 50-50 and MC-MI conditions,  $F(1, 168) = 6.80$ ,  $p = .010$ ,  $\eta^2_p = .04$ , and between the 50-50 and MI-MC conditions,  $F(1, 168) = 15.38$ ,  $p < .001$ ,  $\eta^2_p = .08$ , indicating that the PC effect was not explained by practice with the task. For RTs in the 50-50 condition, there was no significant decrease of interference from the first block (160 ms) to the second block (139 ms),  $F(1, 168) = 0.82$ ,  $p = .366$ ,  $\eta^2_p = .00$ , showing no substantial effect of practice in the absence of a PC manipulation. In the MC-MI condition, interference significantly decreased from the first block (297 ms) to the second block (142 ms),  $F(1, 168) = 39.60$ ,  $p < .001$ ,  $\eta^2_p = .19$ , reflecting the expected PC effect; likewise, in the MI-MC condition, interference significantly increased from the first block (127 ms) to the second block (191 ms),  $F(1, 168) = 7.82$ ,  $p = .006$ ,  $\eta^2_p = .04$ , reflecting the same effect (see Figure 3a).

For error rates, interference significantly decreased from the first block to the second block for both the 50-50 condition,  $F(1, 168) = 7.76$ ,  $p = .006$ ,  $\eta^2_p = .04$ , and the MC-MI condition,  $F(1, 168) = 35.99$ ,  $p < .001$ ,  $\eta^2_p = .18$ , but it decreased significantly more in the MC-MI condition than in the 50-50 condition,  $F(1, 168) = 5.81$ ,  $p = .017$ ,  $\eta^2_p = .03$ , indicating that the PC effect in the MC-MI condition was not explained by simple practice. Interference marginally increased from the first block to the second block for the MI-MC condition,  $F(1, 168) = 2.93$ ,  $p = .089$ ,  $\eta^2_p = .02$ , also reflecting a marginal PC effect, and this pattern significantly differed from the 50-50 condition,  $F(1, 168) = 10.15$ ,  $p = .002$ ,  $\eta^2_p = .06$ .

[Insert Figure 3 approximately here]

## Discussion

Experiment 1 showed the predicted PC effect for both RTs and error rates, indicating reduced interference in a MI block when compared to a MC block. This PC effect was not moderated by age and remained significant when considering specifically the 5-6 years old group; besides, it was not explained by simple practice with the task, suggesting that it reflected a true modulation of cognitive control in the two task blocks. In other words, these results suggested that children were capable of implicitly learning the regularity of conflict in a block of trials, and of using this learned information about conflict as a basis to implement cognitive control when the task required it to a greater extent.

The significant interaction with task block order also showed the expected asymmetrical list shifting effect (Abrahamse et al., 2013). Children who performed the MC block first experienced a large decrease of interference when performing the MI block afterwards; conversely, for children who performed the MI block first, interference increased to a lesser extent when performing the MC block, for both RTs and error rates, suggesting that these subjects transferred the heightened cognitive control settings learned in the first MI

block to the second MC block. This pattern clearly rules against the interpretation that the observed PC effect could be due to learned contingencies, and instead suggests that children did indeed implement a form of cognitive control.

Because the design of Experiment 1 confounded LWPC and ISPC manipulations (with biased items within biased task blocks), it showed that children were capable of adjusting cognitive control engagement to task demands, but the results made it impossible to tell whether the need for control was indexed in a global (proactive) or item-specific (reactive) fashion. The next step was to determine whether the control adjustments observed here were due to proactive control, as reflected in an LWPC effect (Experiments 2a and 2b), and/or to reactive control, as reflected in an ISPC effect (Experiments 3a and 3b).

### **Experiment 2a: LWPC Effect in the Stroop Task**

Experiment 2a investigated whether preschoolers were capable of using proactive control when triggered based on implicit learning in a Stroop-like task, as reflected in an LWPC effect deconfounded from item-specific influences. If implicit proactive control can be detected in preschoolers, this can be seen as evidence that implicit and explicit proactive control are functionally dissociable: if implicit control behaved like explicit control, the LWPC effect should be small to non-existent in preschoolers, and should be significantly larger in a 8-10 years old group.

To test these questions, we used the same fruit Stroop task as Experiment 1, with a modified design comprising both inducer items (biased items, mostly congruent in the MC block and mostly incongruent in the MI block) and diagnostic items (50% congruent in both task blocks). This design has been used in past studies to provide evidence that "pure" proactive control is operating (for a review, see Braem et al., 2019; see also Bugg, 2014a; Bugg & Chanani, 2011; Bugg & Gonthier, 2020; Gonthier, Braver, et al., 2016; Hutchison,



2011). The rationale is that diagnostic items have the same PC for the MC and MI blocks: reduced interference on diagnostic items in the MI block therefore constitutes evidence that subjects implement cognitive control proactively, or in other words, globally - for all items in the block.

Designs with inducer and diagnostic items typically require at least five or six different items: this is because there needs to be at least three or four possible responses for items in the inducer set to prevent contingency learning of stimulus-response associations, and incongruent trials of the inducer set should not ideally include features from the diagnostic set as the irrelevant dimension, so as to avoid transfer of item-specific control settings (Braem et al., 2019; Bugg & Gonthier, 2020). Unfortunately, our fruit Stroop task was limited to four different items (it was difficult to find other stimuli that would be unambiguous for 5-6 years old children<sup>3</sup>, and we expected learning manual response mappings to be difficult for children this age with more than four response options). For this reason, we used the solution proposed in a prior study for the four-arrows version of the flanker task (Bugg & Gonthier, 2020, Experiment 3), in which some incongruent trials of the inducer and diagnostic sets included features from the other set, but the analysis was restricted to congruent trials and to incongruent trials where the two sets did not overlap. This design preserves the fact that there are always four possible responses to all items, which substantially limits the possibility of contingency learning (Braem et al., 2019). It does not quite rule out alternative explanations based on subjects transferring the learned likelihood of conflict from inducer to diagnostic trials (due to features of diagnostic trials appearing as the

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<sup>3</sup> Appropriate stimuli for the task require a fruit or vegetable that children know well and that is easy to identify as a line-drawing shape, and a color that children know how to name and that is easy to discriminate perceptually; moreover, the canonical color of the fruit/vegetable should be non-ambiguous. In a food-related task, these constraints exclude most possible stimuli and colors (for example, blueberries are blue but their shape is ambiguous, apples can be red/yellow/green, and chocolate can be white/brown/black). We pilot tested a few other stimuli but they failed to meet all constraints.

irrelevant dimension on inducer trials), but this represented the best available solution for preschoolers (for a discussion, see Bugg & Gonthier, 2020).

## **Method**

### ***Sample Size***

The only study with a similar design attempting to find a pure LWPC effect with a four-stimuli set in adults recruited 20 subjects and found  $\eta^2_p = .29$  (Bugg & Gonthier, 2020); other studies testing for a pure LWPC effect in adults have observed effect sizes in the same range ( $\eta^2_p$  between .19 and .43 for Bugg, 2014a; Bugg & Chanani, 2011; Gonthier et al., 2016). A power analysis using G\*Power 3.1.9.4 (Faul et al., 2007) indicated that 23 subjects were required to find a .29 effect with .80 power. Given the uncertainties regarding the possibility of observing a pure LWPC effect in preschoolers, we decided to collect double this sample size in each group. Data collection was thus planned for two classes per age group (about 50 children per group, or 100 children total). This was comparable to Experiment 1, not counting the neutral 50-50 condition (Experiment 1 included  $n = 57$  children in the 5-6 years old group for the MC and MI conditions).

### ***Participants***

A sample of 81 children participated in the study. This sample comprised 42 children in kindergarten (19 females and 23 males; mean age = 5.54 years, range = 5.04 to 6.03 years) and 39 children in 4<sup>th</sup> grade (19 females and 20 males; mean age = 9.75 years, range = 8.99 to 10.64 years). Inclusion criteria and features of the sample were the same as in Experiment 1.

### ***Materials, Procedure and Data Processing***

The materials for the Stroop task, testing procedure and data processing were all similar to Experiment 1 (see Figure 1a), except that all children completed an MC block and an MI block, for a total of 192 critical trials. There was one break per block and one between

blocks. The order of the two task blocks was counterbalanced across children in each age group.

Due to the modified design with sets of inducer and diagnostic items, response mappings were changed (*s* for red, *d* for green, *k* for yellow, *l* for orange) so that hands (left hand vs. right hand) and fingers (index vs. middle finger) used to respond were counterbalanced for the set of fruits (red/yellow) and vegetables (green/orange). The familiarization phase was also slightly changed from Experiment 1. As in Experiment 1, there were first 8 trials where children responded to colors and 8 trials where they indicated the canonical color of black-and-white fruits. Children then completed 4 practice trials (2 congruent and 2 incongruent trials). During this familiarization phase, the experimenter had to manually proceed to the next trial, which allowed for clarification of the instructions when needed. Children then completed 16 training trials (proceeding without experimenter input; 50% congruent), which could be restarted if they still had difficulty grasping the instructions, before proceeding to the main task.

### *Design*

Each block comprised 98 trials, with one break; the first trial of a block and the first trial after the break were discarded, leaving 96 critical trials per block. The MC block included 67% of congruent trials and the MI block included 33% of congruent trials. Two of the four drawings were used as diagnostic items, which were 50% congruent in each block, and the two others drawings were used as inducer items (75% congruent in the MC block and 25% congruent in the MI block) to create the list-wide bias. The two sets were counterbalanced across subjects (fruits and vegetables were kept in the same set: the diagnostic set was strawberry and banana for half the children in each age group, carrot and salad for the other half). This design is summarized in Table 3. Trials were presented in the same pseudorandom order for all participants, controlling for repetitions on consecutive trials

(the same trial was never repeated, there were never more than two repetitions of the same fruit, more than four repetitions of the same trial type - congruent or incongruent, and never more than four repetitions of the same item set) and negative priming (the correct response on a trial was never the same as the irrelevant displayed color on the previous trial).

[Insert Table 3 approximately here]

## Results and Discussion

Two children in the 9-10 years old group were excluded (one with a Stroop effect more than 3SD from the mean and one with an error rate above 50%), yielding a final sample size of  $N = 79$  ( $n = 42$  in the 5-6 years old group and  $n = 37$  in the 9-10 years old group). Descriptive statistics for all measures are displayed in Table 4.

[Insert Table 4 approximately here]

The first analysis verified that a LWPC effect appeared for RTs on inducer items, as a manipulation check. The second analysis tested the critical question of whether the LWPC effect existed for diagnostic items (restricted to items from the same set; Bugg & Gonthier, 2020), for both RTs and error rates. Analyses were performed using a 2 (list-wide proportion congruency: MC vs. MI) x 2 (trial type: congruent vs. incongruent) x 2 (age group) x 2 (task block order: MC-MI vs. MI-MC) mixed-design ANOVA.

For inducer items, there was the expected effect of trial type indicating faster RTs for congruent trials,  $F(1, 75) = 114.88$ ,  $p < .001$ ,  $\eta^2_p = .61$ . This effect interacted with list-wide PC,  $F(1, 75) = 27.89$ ,  $p < .001$ ,  $\eta^2_p = .27$ , indicating that interference was reduced in the MI condition when compared to the MC condition as expected. The main effect of age was significant,  $F(1, 75) = 110.44$ ,  $p < .001$ ,  $\eta^2_p = .60$ , indicating faster response times for older children, but there were no interactions involving age; in particular, the three-way interaction between age, list-wide PC and trial type was non-significant,  $F(1, 75) = 0.58$ ,  $p = .447$ ,

$\eta^2_p = .01$ . The three-way interaction between list-wide PC, trial type and task block order was significant,  $F(1, 75) = 5.71, p = .019, \eta^2_p = .07$ , indicating that the difference between the MC and MI blocks was greater in the MC-MI order (158 ms) than in the MC-MI order (59 ms), as in Experiment 1; there were no other interactions involving task block order.

For RTs on diagnostic items, there was the expected effect of trial type,  $F(1, 75) = 46.34, p < .001, \eta^2_p = .38$ ; critically, trial type interacted with list-wide PC,  $F(1, 75) = 5.37, p = .023, \eta^2_p = .07$ , indicating reduced interference in the MI condition when compared to the MC condition. This LWPC effect is represented in Figure 4a. Again, older children had significantly faster RTs,  $F(1, 75) = 114.95, p < .001, \eta^2_p = .61$ , but age did not moderate the LWPC effect,  $F(1, 75) = 0.89, p = .347, \eta^2_p = .01$ . Analyzing log-transformed RTs confirmed this conclusion,  $F(1, 75) = 0.13, p = .716, \eta^2_p = .00$ . The three-way interaction between PC, trial type and task block order was non-significant,  $F(1, 75) = 0.03, p = .854, \eta^2_p = .00$ , as was the four-way interaction with age. For error rates on diagnostic items, there was the expected effect of trial type,  $F(1, 75) = 31.23, p < .001, \eta^2_p = .29$ , but no other effects were significant, all  $ps > .25$ . Error rates are displayed in Figure 4b.

[Insert Figure 4 approximately here]

In summary, Experiment 2a found an LWPC effect for RTs on the critical set of diagnostic items (without overlap between the inducer and diagnostic sets), which were 50% congruent in both task blocks. Thus, this LWPC effect was not confounded with an ISPC manipulation allowing for reactive control, supporting the possibility that these children applied global cognitive control at the list level after implicitly learning its overall proportion congruency. The LWPC effect was not moderated by age, was descriptively stronger in the 5-6 years old group than in older children, and was significant even when considering only the 5-6 years old group, an age where children are expected to rely primarily on reactive control (Gonthier et al., 2019). This finding warranted replication in Experiment 2b, which was also

the opportunity to extend our conclusions to a different task more in line with the adult literature: the flanker task.

Another motivation for Experiment 2b was to test again for the asymmetrical list shifting effect. In this experiment, the LWPC effect on inducer items interacted with task block order as predicted, but the LWPC effect on diagnostic items did not. Finding this interaction for inducer items confirms that the observed PC effects were certainly due to a form of implicit control (Abrahamse et al., 2013), but finding the same interaction for diagnostic items would have constituted additional evidence that the observed effect indeed reflected implicit *proactive* control. It would be difficult to interpret an asymmetrical list shifting effect for inducer, but not diagnostic items, in terms of contingency learning (and our design with four possible responses to all items makes this mechanism unlikely): we believe the most likely explanation for the non-significant interaction was the small effect size for the LWPC effect on diagnostic items ( $\eta^2_p = .07$ , below usual effect sizes in adults), which made it difficult to observe a moderation of this effect by list order. Extending our results to the flanker task in Experiment 2b provided another opportunity to test for the asymmetrical list shifting effect, given that this task has been used to observe a large effect size for the LWPC effect on diagnostic items using the same design (Bugg & Gonthier, 2020).

### **Experiment 2b: LWPC Effect in the Flanker Task**

Experiment 2b attempted to replicate the result of an LWPC effect for diagnostic items found in Experiment 2a, in a different task. We chose to use the arrows flanker task, for a number of reasons: it is a classic and straightforward conflict task that works well with children (Rueda et al., 2004), it has been used to evidence LWPC effects in adults (Bugg & Gonthier, 2020), and the fact that stimuli are directional arrows means that stimulus-response mappings can be transparent for children (e.g. press the left key if the stimulus is a left

arrow). As in Experiment 2a, a design with a set of inducer items and a set of diagnostic items required a bare minimum of four items; for this reason, we used the four-modality version of the task, as in prior studies with adults (Bugg, 2015; Bugg & Gonthier, 2020). The design was exactly identical to Experiment 2a: to create the lists of stimuli, fruits and their displayed colors were just replaced by central and flanker arrows.

We also introduced two refinements to this replication experiment. To extend the findings of Experiment 2a, we were interested in testing whether children were aware of the PC manipulations and their impact on interference. Demonstrating that children are unable to tell the difference between MC and MI task blocks would strongly support the idea that their implementation of cognitive control is indeed implicit - guided by implicit learning of conflict regularity in the task, rather than intentionally implemented in a top-down fashion. Prior studies have shown that subjects are typically unaware of PC manipulations (Blais et al., 2010; Crump et al., 2008), and we expected to find the same result here. Contrary to adults, it was difficult to find a way to query 5-6 years old children on their estimation of proportion congruency in a given task block; as a proxy, we had children estimate the perceived difficulty of MC and MI blocks.

A more secondary change from Experiment 2a was based on our dissatisfaction with the data processing criterion of excluding RTs greater than 3000 ms: younger children tend to have slower RTs, and filtering of RTs should ideally be tailored to a subjects' age. In Experiment 2b, we used a subject-specific threshold for maximal allowed RTs (computed from a subject's median RT and median absolute deviation). Subjects were warned that they had to respond quickly, and received feedback when they responded too slowly, as is usually done with AX-CPT paradigms in children (e.g. Chatham et al., 2009; Gonthier et al., 2019).

## **Method**

### ***Sample Size***

For this conceptual replication of Experiment 2a, constraints on data collection imposed a smaller sample of one class per age group (about 25 children per group, or 50 children total). This seemed to be an adequate compromise given both the results of Experiment 2a (observed  $\eta^2_p = .07$  for the LWPC effect, requiring 108 subjects for .80 power) and the results of the one adult study using exactly the same design and the same flanker task as Experiment 2b (Bugg & Gonthier, 2020; observed  $\eta^2_p = .29$ , requiring 23 subjects for .80 power).

### ***Participants***

A sample of 53 children participated in the study. This sample comprised 27 children in kindergarten (13 females and 14 males; mean age = 5.52 years, range = 4.92 to 5.83 years) and 26 children in 4<sup>th</sup> grade (15 females and 11 males; mean age = 9.40 years, range = 8.91 to 10.00 years). Inclusion criteria and features of the sample were the same as in Experiment 1.

### ***Materials***

The flanker task was presented to children as helping an archer fire arrows in the correct direction, and illustrated with pictures of an archery target and a forest, on a green background. It was programmed in E-Prime and presented on a laptop with a 15-inches screen. Children were seated 43 centimeters from the screen. Each trial began with a fixation cross (+) displayed for 850 ms in the center of the screen, followed by the stimulus which remained on the screen until response (see Figure 1b). Stimuli were sets of five arrows presented in the center of the screen. The set of arrows spanned 8.84° of visual angle (1.6° per arrow and 0.21° between each arrow; based on Rueda et al., 2004). Arrows could go in four directions ( $\wedge$ > $\vee$ <). On congruent trials the central arrow matched the flanker arrows (e.g.



>>>>>), whereas on incongruent trials the central arrow conflicted with the flanker arrows (e.g. >>^>>). Children were instructed to press the numpad key corresponding to the direction of the central arrow (4 key for a left arrow, 6 for a right arrow, 2 for a down arrow and 8 for an up arrow), while ignoring the flanker arrows. Response keys were signaled by stickers with drawings of arrows. Children had to answer using the index finger of their dominant hand, and to move their index finger back to a neutral position (5 key on the numpad) between each trial.

Children were instructed to respond as quickly and accurately as possible. In order to emphasize the need for responding quickly, a threshold for the maximum allowed RT was defined on a subject-per-subject basis. This threshold was computed as (median RT + 3 \* median absolute deviation), with a maximum of 3500 ms. The threshold was recalculated after each trial based on all prior trials (for the first trials, it was calculated based on RTs during training). During the task, children received an auditory feedback after each trial indicating whether their response was too slow ("tick-tock" sound), or if it was within the RT threshold, whether it was correct ("woohoo" sound) or incorrect ("buzz" sound; adapted from Rueda et al., 2004). (Note that the stimulus always remained on-screen until response; the threshold for maximum allowed RT only affected which feedback was given.)

### ***Design***

The design was identical to Experiment 2a (see Table 3).

### ***Procedure***

As in Experiment 2a, children were tested individually in a quiet room at their school. They also completed an MC block and an MI block, for a total of 192 critical trials, with task block order counterbalanced across subjects within each age group. There was again one

break per block and one between blocks, and the whole procedure also lasted approximately 20 to 30 minutes.

The familiarization phase was slightly different from Experiment 2a. It included 4 trials acquainting children with how to respond to a central arrow presented alone by pressing the corresponding key, 4 trials requiring them to respond to a central arrow accompanied by to-be-ignored flankers (2 congruent and 2 incongruent trials), a demonstration of the 3 possible feedbacks, and lastly 4 practice trials with feedbacks (2 congruent and 2 incongruent trials). During this familiarization phase, the experimenter had to manually proceed to the next trial, which allowed for clarification of the instructions when needed. Children then completed 16 training trials (proceeding without experimenter input; 50% congruent), which could be restarted if they still had difficulty grasping the instructions, before proceeding to the main task.

In order to assess awareness of the LWPC manipulation, children were requested to rate the perceived difficulty of the task twice during each block (once after half the trials immediately before the break, and once at the end of the block). Ratings were given using a four-point Likert scale (from 1 = very difficult to 4 = very easy) illustrated with smiley faces (very sad, sad, happy, very happy).

### ***Data Processing***

The data processing was identical to Experiments 1 and 2a, except that trials were excluded when the RT was greater than the subject-specific threshold (see Materials), rather than a fixed threshold of 3000 ms.

### **Results and Discussion**

Four children were excluded with the same criteria as in other experiments (one child in each group with a flanker effect more than 3SD from the mean and one child in each group

with error rates above 50%). Seven additional children in the 5-6 years old group had less than two correct trials within the RT threshold for diagnostic items (on incongruent trials restricted to the same set, the condition with the least trials), and were also excluded. This yielded a final sample size of  $N = 42$  ( $n = 18$  in the 5-6 years old group and  $n = 24$  in the 9-10 years old group). Descriptive statistics for all measures are displayed in Table 5. The results were analyzed in the same way as for Experiment 2a.

[Insert Table 5 approximately here]

For inducer items, there was the expected effect of trial type indicating faster RTs for congruent trials,  $F(1, 38) = 46.01$ ,  $p < .001$ ,  $\eta^2_p = .55$ , and this effect interacted with list-wide PC,  $F(1, 38) = 19.25$ ,  $p < .001$ ,  $\eta^2_p = .34$ , indicating that interference was reduced in the MI condition when compared to the MC condition. The main effect of age was significant,  $F(1, 38) = 43.53$ ,  $p < .001$ ,  $\eta^2_p = .53$ , indicating faster response times for older children, but the three-way interaction between age, PC and trial type was non-significant; this suggested that the magnitude of the PC effect did not differ as a function of age,  $F(1, 38) = 2.62$ ,  $p = .114$ ,  $\eta^2_p = .06$ . The three-way interaction between PC, trial type and task block order was also non-significant,  $F(1, 38) = 2.51$ ,  $p = .122$ ,  $\eta^2_p = .06$ .

For RTs on diagnostic items, there was the expected effect of trial type,  $F(1, 38) = 31.61$ ,  $p < .001$ ,  $\eta^2_p = .45$ , which interacted with list-wide PC,  $F(1, 38) = 5.34$ ,  $p = .026$ ,  $\eta^2_p = .12$ , indicating reduced interference in the MI condition when compared to the MC condition. The effect was of substantially larger magnitude than in Experiment 2a. This LWPC effect is represented in Figure 5a. Again, older children had significantly faster RTs,  $F(1, 38) = 47.96$ ,  $p < .001$ ,  $\eta^2_p = .56$ , but age did not moderate the LWPC effect,  $F(1, 38) = 1.60$ ,  $p = .214$ ,  $\eta^2_p = .04$ . Analyzing log-transformed RTs also showed a non-significant interaction with age,  $F(1, 38) = 1.51$ ,  $p = .227$ ,  $\eta^2_p = .04$ .

Contrary to Experiment 2a, the three-way interaction between PC, trial type and task block order was significant as predicted,  $F(1, 38) = 13.87, p < .001, \eta^2_p = .27$ , indicating that the LWPC effect (the difference of interference on diagnostic items between the MC and MI blocks) was greater in the MC-MI condition (169 ms) than in the MI-MC condition (37 ms). This was compatible with an asymmetrical list shifting effect, reflecting a transfer of control from the MI to the MC block. The four-way interaction with age was also significant,  $F(1, 38) = 7.87, p = .008, \eta^2_p = .17$ , indicating that this pattern was more pronounced in the 5-6 year old group.

For error rates on diagnostic items, the expected effect of trial type was marginally significant,  $F(1, 38) = 3.64, p = .064, \eta^2_p = .09$ , and there was a significant moderation by list-wide PC,  $F(1, 38) = 5.16, p = .029, \eta^2_p = .12$ , indicating that the difference between congruent and incongruent trials was greater in the MC block than in the MI block. This LWPC effect is represented in Figure 5b. The three-way interaction between the LWPC effect and age was non-significant,  $F(1, 38) = 0.11, p = .744, \eta^2_p = .00$ , as were the three-way interaction with task block order and the four-way interaction, both  $ps > .500$ .

[Insert Figure 5 approximately here]

Awareness of the LWPC manipulation was analyzed by averaging the two difficulty ratings obtained for each block, and comparing the MC and MI blocks (given the ordinal nature of these data, we used Wilcoxon's signed-rank test). Overall, children seemed to have little awareness of the LWPC manipulation. The task was perceived as very easy in both the MC blocks (median = 3.50 out of 4) and the MI blocks (median = 3.50 out of 4), and the difference between the two was not significant,  $Z = 1.37, p = .171$ . The same was true when considering separately the 5-6 years old group,  $Z = 0.53, p = .594$ , and the 9-10 years old group,  $Z = 1.41, p = .158$ .

In summary, the results of Experiment 2b essentially replicated Experiment 2a: children demonstrated an LWPC effect on diagnostic items, for both RTs and error rates. Again, this LWPC effect was not significantly moderated by age, and it was significant in the 5-6 years old group (and descriptively stronger than in the 9-10 years old group). Contrary to Experiment 2a, we also found the predicted interaction with task block order, so that the LWPC effect was stronger when the MI block followed the MC block, especially in the 5-6 years old group; again, this asymmetric list shifting effect is more consistent with an actual modulation of proactive control than with contingency learning (Abrahamse et al., 2013). Children were apparently unaware of the LWPC manipulation, supporting the idea that this implementation of proactive control was driven by implicit learning of control settings tailored to the requirements of a given task block.

### **Experiment 3a: ISPC Effect in the Stroop Task**

Experiment 3a investigated whether children could use reactive control based on implicit learning in a Stroop-like task, as reflected in an ISPC effect in a situation that did not allow for control to be applied globally to all items in a block. To this end, we used the same task as Experiment 2a, but with a different design where PC was varied at the item level: task blocks were all 50% congruent and comprised a mix of MC items and MI items (see Bugg et al., 2011). Contrary to the LWPC manipulation, testing the ISPC effect does not require inducer and diagnostic items, and the sets of MC and MI items are allowed to overlap; therefore, four items are sufficient (Braem et al., 2019). Our design also indexed ISPC with the relevant dimension of stimuli (the identity of the fruit, not its displayed color): this approach ensures that the ISPC effect is not driven by contingency learning (for a detailed explanation, see Bugg et al., 2011).

### **Method**

### *Sample Size*

Adult studies using a similar design to test for an ISPC effect have typically reported large effect sizes (e.g.  $\eta^2_p$  between .28 and .67 for Blais & Bunge, 2010; Bugg et al., 2011; Bugg & Hutchison, 2013; Gonthier et al., 2016). The smallest effect size in this range,  $\eta^2_p = .28$ , required 24 subjects to achieve .80 power. As we expected a robust ISPC effect regardless of age, we decided to collect this sample size in each group. Data collection was thus planned for one class per age group (about 25 children per group, or 50 children total).

### *Participants*

A sample of 43 children participated in the study. This sample comprised 17 children in kindergarten (9 females and 8 males; mean age = 5.63 years, range = 5.13 to 6.15 years) and 26 children in 4<sup>th</sup> grade (13 females and 13 males; mean age = 9.82 years, range = 9.01 to 10.95 years). Inclusion criteria and features of the sample were the same as in Experiment 1.

### *Materials, Procedure and Data Processing*

The materials for the Stroop task, testing procedure and data processing were all identical to Experiment 2a (see Figure 1a), except that children completed two 50% congruent blocks.

### *Design*

Subjects completed two identical blocks of 98 trials, with one break per block and between blocks. The first trial of a block and the first trial after the break were discarded, leaving 96 critical trials per block. The blocks included 50% of congruent trials. Two of the four drawings were assigned to be MC items (75% congruent), and the two others were MI items (25% congruent). The two sets were counterbalanced across subjects (the MC set was strawberry and banana for half the children in each age group, carrot and salad for the other

half). This design is summarized in Table 6. Trials were presented in pseudorandom order, with the same controls as in Experiments 2a and 2b.

[Insert Table 6 approximately here]

## Results and Discussion

No child was excluded from the sample. Descriptive statistics for all measures are displayed in Table 7. Analyses were performed using a 2 (item-specific proportion congruency: MC vs. MI) x 2 (trial type: congruent vs. incongruent) x 2 (age group) mixed-design ANOVA.

[Insert Table 7 approximately here]

For RTs, the effect of age was significant, indicating faster RTs for the 9-10 years old group,  $F(1, 41) = 94.96, p < .001, \eta^2_p = .70$ . The expected main effect of trial type was also significant, indicating faster RTs for congruent trials,  $F(1, 41) = 114.16, p < .001, \eta^2_p = .74$ . The predicted interaction with item-specific PC was significant,  $F(1, 41) = 4.35, p = .043, \eta^2_p = .10$ , reflecting an ISPC effect. The three-way interaction between item-specific PC, trial type and age was significant,  $F(1, 41) = 4.07, p = .050, \eta^2_p = .09$ ; it is represented in Figure 6a. Decomposing this interaction with a contrast analysis indicated that the ISPC effect was significant for the 5-6 years old group (109 ms effect),  $F(1, 41) = 6.96, p = .012, \eta^2_p = .15$ , but not for the 9-10 years old group (2 ms effect),  $F(1, 41) = 0.00, p = .958, \eta^2_p = .00$ . The same three-way interaction did not reach significance when analyzing log-transformed RTs,  $F(1, 41) = 2.31, p = .136, \eta^2_p = .05$ .

For error rates, there was a significant effect of trial type,  $F(1, 41) = 76.51, p < .001, \eta^2_p = .65$ , reflecting higher error rates for incongruent trials. The two-way interaction with item-specific PC was also significant,  $F(1, 41) = 4.53, p = .039, \eta^2_p = .10$ , reflecting greater interference for MC items than for MI items; this ISPC effect is represented in Figure 6b. The

effect of age was not significant,  $F(1, 41) = 2.62$ ,  $p = .113$ ,  $\eta^2_p = .06$ , and neither was the three-way interaction between PC, trial type and age,  $F(1, 41) = 0.03$ ,  $p = .867$ ,  $\eta^2_p = .00$ .

[Insert Figure 6 approximately here]

In summary, Experiment 3a revealed an ISPC effect for the 5-6 years old group, which could not be driven by block-level conflict monitoring since all task blocks were 50% congruent. The results thus indicated that children were capable of learning the probability of conflict on an item-by-item basis, and to dynamically tailor cognitive control engagement accordingly. As expected, the ISPC effect was significant in the 5-6 years old group, but contrary to our expectations, it was not significant for RTs in the 9-10 years old group. Experiments 2a and 2b had also found a descriptively stronger effect in the 5-6 years old group, but contrary to these prior experiments, however, in Experiment 2b the interaction with age was significant and the ISPC effect was descriptively null (2 ms, see Table 7) in the 9-10 years old group for RTs.

Given that there is no theoretical reason that the ISPC pattern should disappear with age (since it is robustly observed in adults), two explanations seem plausible: first, random variation may have masked the effect in the older group, due to the combination of faster RTs, large standard deviations and low sample size. (Because 9-10 years old children are more variable than adults, with standard deviations in the 175 ms to 250 ms range, it may be difficult to detect significant PC effects in this group even with sample sizes similar to adult studies). The fact that the ISPC effect was not moderated by age when analyzing log-transformed RTs (expressing interference as a proportion of congruent RTs) tends to support this conclusion. Second, based on the fact that the ISPC effect for error rates was not significantly moderated by age and was descriptively similar in the two age groups (see Figure 6b), it may be the case that the effect of the ISPC manipulation was mainly apparent in error rates in the older age group (e.g. due to a different speed-accuracy tradeoff). As for



Experiments 2a and 2b, we conducted another experiment to replicate and extend the findings of Experiment 3a in a flanker task.

### **Experiment 3b: ISPC Effect in the Flanker Task**

Experiment 3b was a conceptual replication of Experiment 3a using the arrows flanker task - symmetrical with Experiments 2a and 2b. Our main objective was to replicate and extend the finding of an ISPC effect in the 5-6 years old group to a different task. Experiment 3b used the same flanker task as Experiment 2b and the same ISPC design as Experiment 3a. The modifications introduced for Experiment 2b were also applied here: we tested whether children were aware of the ISPC manipulation by asking them to indicate which item set they felt was more difficult; and we used a subject-specific RT threshold to exclude slow trials.

### **Method**

#### *Sample Size*

Data collection in this conceptual replication of Experiment 3a was again planned for one class per age group (about 25 children per group, or 50 children total). The  $\eta^2_p = .15$  effect size obtained in Experiment 3a was lower than those reported in the literature, but only required 48 subjects for .80 power.

#### *Participants*

A sample of 54 children participated in the study. This sample comprised 28 children in kindergarten (13 females and 15 males; mean age = 5.32 years, range = 4.83 to 5.83 years) and 26 children in 4<sup>th</sup> grade (9 females and 17 males; mean age = 9.38 years, range = 8.75 to 9.75 years). Inclusion criteria and features of the sample were the same as in Experiment 1.

#### *Materials, Procedure and Data Processing*

The materials for the flanker task, testing procedure and data processing were all identical to Experiment 2b (see Figure 1b), except for the procedure assessing awareness of the ISPC manipulation. Contrary to Experiment 2b, awareness was tested by asking children whether they felt it was more difficult to respond to the set of up/down arrows, to the set of left/right arrows, or neither. The two sets of arrows were presented on-screen as a visual support. Because the two task blocks were identical and to maximize the chance that children had had time to detect the ISPC manipulation, this question was only asked once at the very end of the task.

### ***Design***

The ISPC design was identical to Experiment 3a (see Table 6).

### **Results and Discussion**

One child in the 9-10 years old group with a flanker effect more than 3SD from the mean was excluded; the final sample size was  $N = 53$  ( $n = 28$  in the 5-6 years old group and  $n = 25$  in the 9-10 years old group). Descriptive statistics for all measures are displayed in Table 8. The results were analyzed in the same way as for Experiment 2b.

[Insert Table 8 approximately here]

For RTs, the effect of age was significant, indicating faster RTs for the 9-10 years old group,  $F(1, 51) = 80.59$ ,  $p < .001$ ,  $\eta^2_p = .61$ . The expected main effect of trial type was also significant, indicating faster RTs for congruent trials,  $F(1, 51) = 97.79$ ,  $p < .001$ ,  $\eta^2_p = .66$ . The predicted interaction with item-specific PC was significant,  $F(1, 51) = 6.64$ ,  $p = .013$ ,  $\eta^2_p = .12$ , reflecting an ISPC effect; this interaction is represented in Figure 7a. The three-way interaction between item-specific PC, trial type and age was not significant,  $F(1, 51) = 1.88$ ,  $p = .177$ ,  $\eta^2_p = .04$ , and remained non-significant when analyzing log-transformed RTs,  $F(1, 51) = 0.15$ ,  $p = .700$ ,  $\eta^2_p = .00$ .

For error rates, there was a significant effect of trial type,  $F(1, 51) = 42.09, p < .001, \eta^2_p = .45$ , reflecting higher error rates for incongruent trials, but the two-way interaction with item-specific PC was non-significant,  $F(1, 51) = 0.53, p = .469, \eta^2_p = .01$ . The effect of age was significant,  $F(1, 51) = 18.76, p < .001, \eta^2_p = .72$ , but the three-way interaction between PC, trial type and age was not,  $F(1, 51) = 0.36, p = .552, \eta^2_p = .01$ . Error rates are represented in Figure 7b.

[Insert Figure 7 approximately here]

Overall, children had little to no awareness of the ISPC manipulation. In the 5-6 years old group, 27 out of 29 children answered that the two sets of items were equally difficult, one child identified the MI set as more difficult and one identified the MC set as more difficult. In the 9-10 years old group, 21 out of 26 children answered that the two sets of items were equally difficult, four children identified the MI set as more difficult and one identified the MC set as more difficult. The difference between groups was not significant,  $\chi^2(2) = 2.39, p = .302$ .

In summary, Experiment 3b replicated the ISPC effect found in Experiment 3a. As in Experiment 2b, children seemed unaware of the PC manipulation, supporting the idea that the observed PC effect was based on implicit learning of the probability of conflict on an item-per-item basis. Contrary to Experiment 3a, the effect did not significantly interact with age and the pattern was descriptively in the expected direction for the 9-10 years old group; the 28 ms ISPC effect found in this group was also consistent with ISPC effects found in adults (e.g. Gonthier, Braver, et al., 2016).

### **General Discussion**

This study performed the first systematic investigation of PC effects in young children. All five experiments showed that preschoolers demonstrated PC effects. Preschoolers demonstrated both LWPC and ISPC effects, in both a Stroop-like and a flanker

task. Evidence for an asymmetrical list shifting effect in Experiments 1 and 2b, and evidence that children were not aware of the PC manipulations in Experiments 2b and 3b, supported the idea that these PC effects reflected a form of implicit cognitive control. These results provide converging evidence that preschoolers are capable of implicitly learning proportion congruency for a given context and regulating cognitive control implementation accordingly - at an age where they have considerable difficulty engaging in explicit cognitive control.

Additionally, PC effects were not moderated by age in four out of five experiments, suggesting that they existed to a similar extent in preschoolers and in older children. The effect sizes for the interaction with age were so small that it would have required very large samples sizes to find a significant interaction ( $\eta^2_p = .00, .01$  and  $.04$ , requiring a minimum of 192 subjects to achieve  $.80$  power). Critically, however, a larger sample size would not have changed our conclusions: in all five studies, PC effects were descriptively larger in preschoolers than in older children. This pattern is sometimes observed in conflict tasks when effects depend on baseline response speed<sup>4</sup> (see Smulders et al., 2018), but it starkly differs with the pattern typically observed for explicit control, and it would be difficult to reconcile with a developmental increase in the effectiveness of the mechanism driving the PC effects.

(Note that a possible issue with these results is that the significant PC effects could have been driven by the 8-9 years old group, but this was not the case: complementary analyses

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<sup>4</sup> To interpret this descriptively larger PC effect in the group with lower ability, it is also worth noting that interference in the two age groups differed to a greater extent in MC conditions than in MI conditions (Tables 4-5 and 7-8). This suggests that younger children were particularly slowed on incongruent trials in the MC block where most trials were congruent, compatible with the phenomenon of goal neglect prevalent in preschoolers; by contrast, they had a pattern closer to older children in MI conditions, where a large proportion of incongruent items served to trigger implicit cognitive control (for similar patterns, see Kane & Engle, 2003; Meier & Kane, 2013; Marcovitch et al., 2007, 2010). In line with this idea, PC effects in preschoolers (Experiment 2a: 126 ms, Experiment 2b: 111 ms, Experiment 3a: 109 ms, Experiment 3b: 89 ms) were much larger than the 30ms to 50ms range typically observed in adults. This suggests the descriptively larger effects in this group could have been due to slower response speed or to more interference in the MC blocks which included few goal reminders.

indicated that the PC effect was significant when considering specifically the 5-6 years old group, in all five studies.)

In sum, in showing that implicit cognitive control is operative in preschoolers and does not seem to improve across childhood, our results support the hypothesis of a functional distinction between implicit and explicit control as proposed by prior studies (Blais et al., 2010; Bugg et al., 2015; Kunde et al., 2012).

### **Towards a Dissociation Between Implicit and Explicit Control**

By themselves, the current results would not be sufficient to claim a dissociation between implicit and explicit cognitive control. Instead, they should be viewed as converging evidence adding to the growing literature that suggests explicitly and implicitly-triggered control behave differently. In the case of conflict tasks and PC effects, other pieces of converging evidence prominently include studies comparing the effects of explicit instructions and implicit PC manipulations, which have shown a limited role of explicit instructions for minimizing interference (Bugg & Smallwood, 2014; Bugg et al., 2015; Entel et al., 2014). Other clues come from studies reporting PC effects in rhesus monkeys (Washburn, 2016), and in older adults (e.g. Bugg, 2014a; Cohen-Shikora et al., 2018).

In particular, one study found evidence for an LWPC effect in older adults who, like preschoolers, have been repeatedly reported not to use explicit proactive control (Cohen-Shikora et al., 2018; but see Bugg, 2014a). Taken together, these results hint at an interesting lifespan trajectory: preschoolers and older adults appear to struggle with explicit control, and particularly explicit proactive control; but preschoolers and older adults reliably demonstrate implicit control, including implicit proactive control.

The finding of an LWPC effect particularly contrasted with the oft-repeated statements that preschoolers have poor cognitive control, and that they do not use proactive control, relying on reactive control instead (Barker & Munakata, 2015; Chevalier, 2015b;

Munakata et al., 2012). In fact, they seem capable of doing so when aided by implicit cues. Our results add to growing evidence that even preschool children may in fact engage in proactive control when the situation provides scaffolding (Chevalier et al., 2015; Elke & Wiebe, 2017). The finding that preschoolers and older adults (Cohen-Shikora et al., 2018) can engage in implicit proactive control thus has particular implications for conceptualizations of proactive control, by suggesting that it is not the ability to implement control in advance as such that varies with age, but the ability to voluntarily trigger this advance preparation based on explicit cues (Cohen-Shikora et al., 2018). In other words, the failure of preschoolers to use proactive control in tasks such as the AX-CPT (Gonthier et al., 2019) would be due to the explicit component required by the task.

Although the AX-CPT and the LWPC effect can both be considered instances of proactive control (Gonthier, Braver, et al., 2016), in unpublished experiments, we and other research teams have failed to find correlations between indices of proactive control as measured with the AX-CPT, and as measured with the LWPC effect in a Stroop task (e.g. Gonthier, 2014). Part of the problem may be caused by the low reliability of cognitive control indices in these two tasks (see Cooper et al., 2017), but the present data suggest that this lack of relation may also be due to meaningful differences in the explicit and implicit mechanisms involved by the AX-CPT and by the LWPC effect.

### **Mechanisms of Implicit and Explicit Cognitive Control**

If implicit control is shown to be distinct from explicit control, then this begs the question of what mechanisms exactly differ between the two forms of control. Models of cognitive control have usually considered the core act of control (the actual biasing, change or regulation of behavior in line with the task goal, once the system has "decided" to engage in control) to be relatively similar whether control is triggered based on explicit or implicit cues (compare e.g. Botvinick et al., 2001, 2004; Braver et al., 2007). This suggests that the

difference lies elsewhere and hinges more on how control is recruited. Investigating what mechanisms drive the difference between implicit and explicit control would be an exciting direction for future research. Developmental data point towards four major possibilities, forming a continuum from cue monitoring, to cue processing and conversion into a task goal, to maintenance of this goal-related information, to implementation of the task goal (see Chevalier, 2015a):

1) A first possibility raised by the developmental literature is that explicit cognitive control places more constraints than implicit control on cue monitoring. Indeed, children seem to have difficulty monitoring for explicit cues and orienting their attention towards cues that are relevant to responding (see Chevalier, 2015a). For example, young children tend to devote more attention to task stimuli than to the cues indicating how they should process them (see Chevalier et al., 2010, 2018; Karbach & Kray, 2007; see also Chevalier, Chatham, et al., 2014). By contrast, task cues in the case of implicit control (errors or experienced conflict) are an intimate part of the subject's subjective experience of the task and should not require additional processing.

2) A second possibility is that explicit control involves more complex processing of task cues than implicit control. Converting a task cue into a goal for action requires a non-trivial cognitive operation that can be difficult even for adults (see Chevalier, 2015a), and can involve recoding through an inner speech process that develops throughout childhood (Cragg & Nation, 2010). It can be difficult for children to convert explicit cues into goals and intentions: for instance, they have difficulties exerting cognitive control when explicit cues on what they should do are arbitrary rather than transparent (i.e. semantically related to the action at hand: for instance, a left arrow to indicate that they should respond to the left stimulus; Blaye & Chevalier, 2011; Chevalier & Blaye, 2009; Towse et al., 2007). By contrast, in the case of implicit control, the cues signaling control demands are unambiguous.

Errors in the case of post-error slowing, and experienced conflict in the case of sequential congruency effects and PC effects, all clearly signal the need for a change of behavior (attenuating processing of the stimulus dimension that led to error or conflict, and/or enhancing processing of the relevant dimension).

3) Third, explicit control may place more demands on active maintenance of the cue or task goal in working memory. Explicit control in general and explicit proactive control in particular have generally been described as requiring active maintenance of goal-related information in working memory (see Braver et al., 2007; Miller & Cohen, 2001; Roberts & Pennington, 1996); for instance, usual paradigms such as cued task-switching require subjects to remember the explicit cue over a few seconds until the stimulus requiring control is presented. Consistent with this idea, the development of explicit proactive control in children has been related to the development of working memory (see Gonthier et al., 2019; Troller-Renfree et al., 2020). This process of active maintenance of an explicit cue may require particular effort, and may be engaged only for highly reliable cues (Bugg et al., 2014, 2015). By contrast, implicit control may not require active, effortful maintenance of goals or cues in working memory: either because goal settings are learned in an implicit form that does not rely on working memory, or because the task goal is automatically reactivated with each occurrence of the errors and conflicts that constitute implicit cues (Kane & Engle, 2003; Marcovitch et al., 2007, 2010).

Note that this idea may be seen as conflicting with the finding that the magnitude of the LWPC effect in the Stroop task correlates with working memory capacity in adults (Hutchison, 2011; Kane & Engle, 2003; Meier & Kane, 2013): if the LWPC effect reflects implicit control and implicit control requires little working memory, why would it correlate with working memory? This can be reconciled by noting that a low working memory capacity is especially related to more word reading in the MC condition, as evidenced by



more facilitation and a higher error rate; by contrast, a low working memory capacity makes little difference for the MI condition (Hutchison, 2011; Kane & Engle, 2003; Meier & Kane, 2013). Thus it could be the case that participants with low working memory (adults, or younger children) struggle with explicit control when most trials are congruent, but can implicitly learn when most trials are incongruent and implicitly heighten cognitive control accordingly, eliciting a large LWPC effect (see also Bugg et al., 2015).

4) Lastly, explicit control may require a more effortful process to convert the task goal into an action. This possibility is grounded in the phenomenon of goal neglect - the observation that subjects sometimes remember what the goal is, but neglect to act according to this goal (Duncan et al., 1996, 2008). This is not quite the same thing as *forgetting* the task goal, partly because there is a subtle nuance between forgetting the task goal altogether and failing to implement the goal on a given trial: goal neglect occurs even when the rules are repeated to subjects on every trial (Marcovitch et al., 2007). Goal neglect has been shown to occur in preschoolers (Marcovitch et al., 2007) and to gradually decrease throughout development (Diamond & Taylor, 1996; Towse et al., 2007; Zelazo, et al., 2003), suggesting that the ability to implement the goal as a concrete action in the task may contribute to the developmental dissociation between explicit and implicit control.

### **Limitations and Directions for Improvement**

The present series of experiments suggests two directions for improvement in future studies interested in implicit control in children. The first relates to the design. The literature has proposed a number of alternative accounts of PC effects (see Braem et al., 2019; for an example, see Schmidt, 2013). We strived to account for most of these possibilities - for example, the pseudorandom order of trials controlled for stimulus repetitions and congruency sequences, and the systematic use of four different items with four possible responses should minimize the role of learning of stimulus-response associations and contingency learning, as

does the indexation of ISPC based on the relevant dimension of stimuli. Experiments 3a and 3b should provide a relatively pure test of the ISPC effect, but it may be possible to improve on the design used for Experiments 2a and 2b, with four items instead of five or six. Indeed, this particular design leaves open the possibility that subjects somehow transferred implicit control from inducer to diagnostic trials (see Bugg & Gonthier, 2020).

Improving on this design with children would require other concessions. It would presumably require another conflict task than the classic flanker task (Rueda et al., 2004) and fruit-color Stroop (Archibald & Kerns, 1999; Macdonald et al., 2015; Okuzumi et al., 2014) used here, both of which were difficult to extend to more than four stimuli. One possible option would be the object-color Stroop (see Prevor & Diamond, 2005), where object-color associations tend to be more ambiguous than fruit-color. It would also require having children learn more than four stimulus-response mappings, which could interfere with the task by imposing a memory load; or using vocal responses, which can be difficult with preschoolers due to interfering noises.

The second possible direction for improvement rests on the fact that we did not directly assess explicit control in our subjects. The developmental literature has abundantly documented the drastic increases of explicit cognitive control from preschooler to teenager age (e.g. Chevalier, 2015a, 2015b; Davidson et al., 2006; Diamond, 2013; Huizinga et al., 2006; Macdonald et al., 2014; Munakata et al., 2012; Zanolie & Crone, 2018; Zelazo et al., 2013), and we specifically targeted the 5-6 years old group because children in this age range have been shown to use little explicit proactive control (Gonthier et al., 2019). However, for a fuller demonstration, it would be even more informative to directly compare the developmental trajectories of the two forms of control in the same subjects. This could be achieved, for example, by using conflict tasks where explicit expectations are conveyed to the subjects (e.g. "the next trial will be conflicting"; Bugg & Smallwood, 2016), allowing for

concurrent manipulation of explicit and implicit control (Bugg et al., 2015; Entel et al., 2014). Given that the precise trajectory of explicit control appears to vary across tasks (e.g. Davidson et al., 2006; Diamond, 2013; Huizinga et al., 2006), it would be ideal to examine the development of the two mechanisms concurrently with the same paradigm.

### **Other Possibilities for Future Research**

Methodologically, a distinction between implicit and explicit control means a closer look into experimental paradigms is necessary to help disentangle the contributions of the two mechanisms. Whether the cue is implicit or explicit influences other aspects of task design, which confounds the comparison between control mechanisms. Examples include the delay between cues and probes, and the ways cues are represented in memory. Paradigms usually used to measure explicit proactive control - such as the AX-CPT and cued task-switching - require subjects to maintain the identity of an arbitrary cue (or a planned action based on this cue) in memory for a few seconds before the probe appears; by contrast, the LWPC effect that represents implicit proactive control requires subjects to maintain control settings (the need for heightened cognitive control) for a few dozens or hundreds of trials. Another complication is that manipulations of explicit proactive control sometimes involve a component of implicit learning: this is the case in paradigms where subjects have to learn implicitly that an explicit cue is not 100% valid (e.g. Bugg & Smallwood, 2014). Another example is the AX-CPT: while primarily intended to measure explicit control, the task also includes a subtle component of implicit learning (subjects have to learn implicitly in the task that X probes often follow A cues). These types of methodological issues could certainly bias comparison between the mechanisms underlying explicit and implicit cognitive control.

Theoretically, it is also worth questioning whether a distinction between implicit and explicit cognitive control would be sufficient to account for the whole spectrum of cognitive control implementation. In particular, a few authors have outlined a third possible form of

control: self-initiated control - in other words, control engaged by the subject without explicit or implicit cues emanating from the task. For instance, developmental studies have suggested that self-initiated control may operate in verbal fluency tasks to drive the subject's decision to switch to a different category (Snyder & Munakata, 2010, 2013); this ability may develop later than other forms of control (Munakata et al., 2012, 2014). In adults, the same idea of self-initiated control has been used to account for specific patterns of impairment in Parkinson's disease (Werheid et al., 2007), and neuroimaging data suggests that self-initiated control may be associated with a specific neural substrate (Forstmann et al., 2006). In fact, the idea of self-initiated control as a different form of control reflects a long-standing criticism about the use of executive functioning tasks in clinical neuropsychology: that these tasks may have poor ecological validity, because they are always performed in a highly structured task environment providing multiple clues about what the subject should be doing; whereas real-life cognitive control is often deployed in situations where subjects have to decide on their own what they should be doing (Chaytor & Schmitter-Edgecombe, 2003; Gioia & Isquith, 2004; Wallisch et al., 2018). Whether self-initiated control actually constitutes a distinct form of control, or whether it is ultimately still triggered by task cues (such as detection that the rhythm of exemplar generation is dropping in a verbal fluency task), remains to be explored.

From a developmental standpoint, our findings provide evidence that young children are capable of surprisingly fine-grained cognitive control adjustments, when these adjustments are triggered by implicit cues. The fact that PC effects were present in the 5-6 years old group in all five experiments and in two different tasks suggests that this skill is already relatively reliable, even early in development. The fact that PC effects did not increase with age could also be seen as converging evidence that behavioral patterns of performance based on implicit cognitive control are relatively invariant throughout

development (Larson et al., 2012; McDermott et al., 2017; Surrey et al., 2019; Wiersema et al., 2017; Wilk & Morton, 2012). On a related note, these results also confirm that preschoolers are capable of monitoring the difficulty of an ongoing task, at least at an implicit level; this is in line with a growing literature demonstrating early metacognitive skills (e.g. Paulus et al., 2013; Roebers, 2017), at least when supported by task cues rather than self-initiated (O'Leary & Sloutsky, 2017). Development of these early skills may constitute a promising area of study.

In keeping with PC effects, a possible direction for developmental research would be to investigate the development of context-specific PC (CSPC) effects. CSPC effects are conceptually similar to LWPC and ISPC effects, except that the PC manipulation is indexed by a stimulus dimension that is incidental to the task, such as font type in a Stroop task (for example, words written in a certain font could be mostly congruent; Bugg et al., 2008). Recent data suggest that young children also demonstrate sensitivity to CSPC effects, as they do to LWPC and ISPC effects (Gonthier & Blaye, 2020). If this indeed proves to be the case, it will constitute further evidence that the mechanisms underlying monitoring and learning of conflict likelihood, and corresponding adjustments of cognitive control, together constitute a robust process that can pick up on subtle environmental cues even in subjects with immature cognitive control and who struggle with voluntary implementation of control.

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Table 1

*Frequency of trial types as a function of task block for Experiment 1*

Task block	Fruit	Displayed color			
		Red	Yellow	Orange	Green
Mostly congruent (MC)	Strawberry	20	1	1	2
	Banana	2	20	1	1
	Carrot	1	2	20	1
	Salad	1	1	2	20
Mostly incongruent (MI)	Strawberry	4	7	6	7
	Banana	7	4	7	6
	Carrot	7	6	4	7
	Salad	6	7	7	4
50% congruent (PC-50)	Strawberry	12	4	4	4
	Banana	4	12	4	4
	Carrot	4	4	12	4
	Salad	4	4	4	12

Table 2

*Descriptive statistics for Experiment 1*

Measure	Condition	Task block	5-6 years old			8-9 years old			
			CON	INC	INT	CON	INC	INT	
RTs	MC then MI	MC (83% congruent)	1467 (227)	1812 (282)	345	1045 (159)	1292 (216)	247	
		MI (17% congruent)	1547 (227)	1731 (199)	184	1104 (185)	1203 (186)	99	
	MI then MC	MC (83% congruent)	1452 (230)	1638 (251)	186	1089 (138)	1287 (212)	198	
		MI (17% congruent)	1579 (223)	1662 (234)	83	1173 (152)	1346 (199)	173	
	PC-50	First block (50% congruent)	1527 (233)	1686 (268)	159	1113 (215)	1274 (267)	161	
		Second block (50% congruent)	1473 (185)	1619 (239)	146	1124 (215)	1254 (258)	130	
	ERs	MC then MI	MC (83% congruent)	.014 (.013)	.144 (.123)	.130	.006 (.011)	.097 (.089)	.091
			MI (17% congruent)	.020 (.036)	.055 (.038)	.035	.000 (.000)	.046 (.037)	.046
MI then MC		MC (83% congruent)	.011 (.013)	.075 (.079)	.064	.005 (.006)	.094 (.089)	.089	
		MI (17% congruent)	.010 (.025)	.062 (.055)	.052	.000 (.000)	.064 (.042)	.064	
PC-50		First block (50% congruent)	.010 (.016)	.097 (.058)	.087	.010 (.013)	.069 (.067)	.059	
		Second block (50% congruent)	.010 (.016)	.051 (.042)	.041	.010 (.012)	.050 (.043)	.040	

*Note.* Averages with standard deviations in parentheses. RTs = Response times, ERs = Error rates, MC = Mostly congruent, MI = Mostly incongruent, PC-50 = 50% congruent, CON = Congruent, INC = Incongruent, INT = Interference (difference between incongruent and congruent).

Table 3

*Frequency of trial types as a function of task block for Experiments 2a and 2b*

Task block	Fruit	Displayed color			
		Red	Yellow	Orange	Green
Mostly congruent (MC)	Strawberry	<b><u>8</u></b>	<b><u>3</u></b>	<b>3</b>	<b>2</b>
	Banana	<b><u>3</u></b>	<b><u>8</u></b>	<b>2</b>	<b>3</b>
	Carrot	2	3	24	3
	Salad	3	2	3	24
Mostly incongruent (MI)	Strawberry	<b><u>8</u></b>	<b><u>3</u></b>	<b>3</b>	<b>2</b>
	Banana	<b><u>3</u></b>	<b><u>8</u></b>	<b>2</b>	<b>3</b>
	Carrot	8	8	8	8
	Salad	8	8	8	8

*Note.* Displayed is one possible counterbalance in which strawberries and bananas are the diagnostic set (in boldface). The critical subtest of diagnostic items that does not include features of the inducer items is underlined. The table displays stimuli for Experiment 2a; the design was identical for Experiment 2b, with fruits and displayed colors replaced by targets and flankers respectively (for example, a strawberry would be a > target and the displayed color red would be >> >> flankers in Experiment 2b).

Table 4

*Descriptive statistics for Experiment 2a*

Measure	Age group	Item type	MC			MI		
			CON	INC	INT	CON	INC	INT
RTs	5-6 years old	Inducer items	1360 (228)	1589 (287)	229	1494 (309)	1575 (289)	81
	5-6 years old	Diagnostic items (same set)	1399 (255)	1639 (369)	240	1440 (319)	1554 (310)	114
	9-10 years old	Inducer items	878 (172)	1063 (222)	185	930 (185)	1033 (210)	103
	9-10 years old	Diagnostic items (same set)	885 (176)	1027 (268)	142	897 (219)	985 (239)	88
ERs	5-6 years old	Inducer items	.014 (.022)	.080 (.089)	.066	.016 (.031)	.064 (.036)	.048
	5-6 years old	Diagnostic items (same set)	.018 (.032)	.081 (.117)	.063	.021 (.041)	.071 (.127)	.050
	9-10 years old	Inducer items	.016 (.020)	.068 (.080)	.052	.024 (.040)	.064 (.046)	.040
	9-10 years old	Diagnostic items (same set)	.027 (.043)	.114 (.138)	.087	.014 (.033)	.088 (.158)	.074

*Note.* Averages with standard deviations in parentheses. RTs = Response times, ERs = Error rates, MC = Mostly congruent, MI = Mostly incongruent, PC-50 = 50% congruent, CON = Congruent, INC = Incongruent, INT = Interference (difference between incongruent and congruent).

Table 5

*Descriptive statistics for Experiment 2b*

Measure	Age group	Item type	MC			MI		
			CON	INC	INT	CON	INC	INT
RTs	5-6 years old	Inducer items	1373 (395)	1517 (426)	144	1414 (454)	1460 (429)	46
	5-6 years old	Diagnostic items (same set)	1466 (394)	1705 (553)	239	1431 (377)	1559 (586)	128
	9-10 years old	Inducer items	794 (147)	886 (144)	91	801 (165)	847 (143)	46
	9-10 years old	Diagnostic items (same set)	820 (148)	919 (154)	99	821 (168)	888 (147)	67
ERs	5-6 years old	Inducer items	.028 (.032)	.059 (.083)	.031	.024 (.055)	.079 (.091)	.055
	5-6 years old	Diagnostic items (same set)	.029 (.040)	.108 (.202)	.079	.025 (.062)	.056 (.162)	.031
	9-10 years old	Inducer items	.012 (.023)	.019 (.040)	.007	.008 (.021)	.025 (.033)	.017
	9-10 years old	Diagnostic items (same set)	.021 (.040)	.058 (.120)	.037	.014 (.047)	.014 (.068)	.000

*Note.* Averages with standard deviations in parentheses. RTs = Response times, ERs = Error rates, MC = Mostly congruent, MI = Mostly incongruent, PC-50 = 50% congruent, CON = Congruent, INC = Incongruent, INT = Interference (difference between incongruent and congruent).

Table 6

*Frequency of trial types as a function of task block for Experiments 3a and 3b*

Item set	Fruit	Displayed color			
		Red	Yellow	Orange	Green
Mostly congruent (MC)	Strawberry	36	4	4	4
	Banana	4	36	4	4
Mostly incongruent (MI)	Carrot	12	12	12	12
	Salad	12	12	12	12

*Note.* Displayed is one possible counterbalance in which strawberries and bananas are the MC set. The table displays stimuli for Experiment 3a; the design was identical for Experiment 3b, with fruits and displayed colors replaced by targets and flankers respectively (for example, a strawberry would be a > target and the displayed color red would be >> >> flankers in Experiment 3b).

Table 7

*Descriptive statistics for Experiment 3a*

Measure	Age group	MC			MI		
		CON	INC	INT	CON	INC	INT
RTs	5-6 years old	1442 (203)	1678 (232)	236	1491 (284)	1618 (245)	127
	9-10 years old	911 (166)	1076 (233)	165	891 (144)	1054 (214)	163
ERs	5-6 years old	.022 (.053)	.074 (.058)	.052	.022 (.021)	.055 (.030)	.033
	9-10 years old	.022 (.024)	.101 (.068)	.079	.022 (.027)	.085 (.049)	.063

*Note.* Averages with standard deviations in parentheses. RTs = Response times, ERs = Error rates, MC = Mostly congruent, MI = Mostly incongruent, PC-50 = 50% congruent, CON = Congruent, INC = Incongruent, INT = Interference (difference between incongruent and congruent).

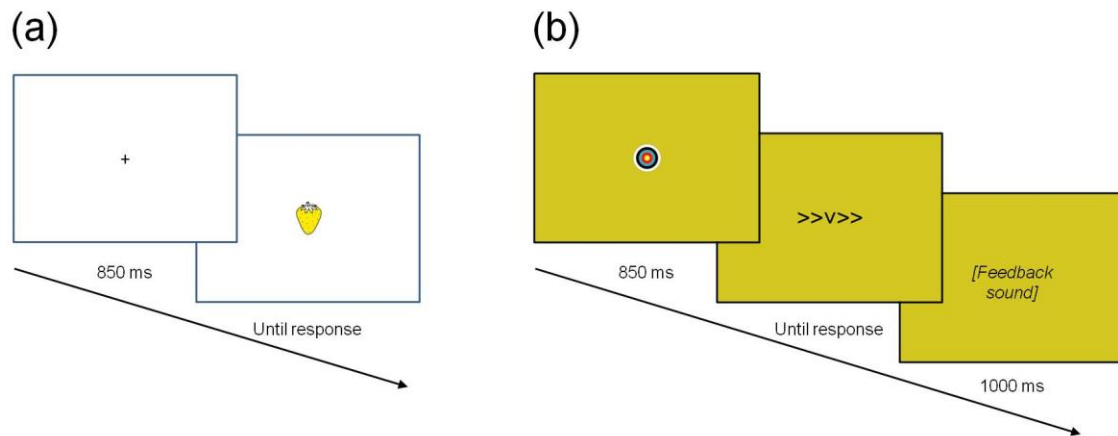
Table 8

*Descriptive statistics for Experiment 3b*

Measure	Age group	MC			MI		
		CON	INC	INT	CON	INC	INT
RTs	5-6 years old	1387 (319)	1570 (392)	183	1384 (382)	1478 (344)	94
	9-10 years old	770 (121)	841 (123)	71	788 (124)	831 (129)	43
ERs	5-6 years old	.035 (.060)	.092 (.090)	.057	.032 (.050)	.091 (.086)	.059
	9-10 years old	.015 (.018)	.015 (.026)	.000	.012 (.023)	.027 (.027)	.015

*Note.* Averages with standard deviations in parentheses. RTs = Response times, ERs = Error rates, MC = Mostly congruent, MI = Mostly incongruent, PC-50 = 50% congruent, CON = Congruent, INC = Incongruent, INT = Interference (difference between incongruent and congruent).





*Figure 1.* Illustration of the experimental displays for (a) Experiment 1, Experiment 2a and Experiment 3a and (b) Experiment 2b and Experiment 3b.

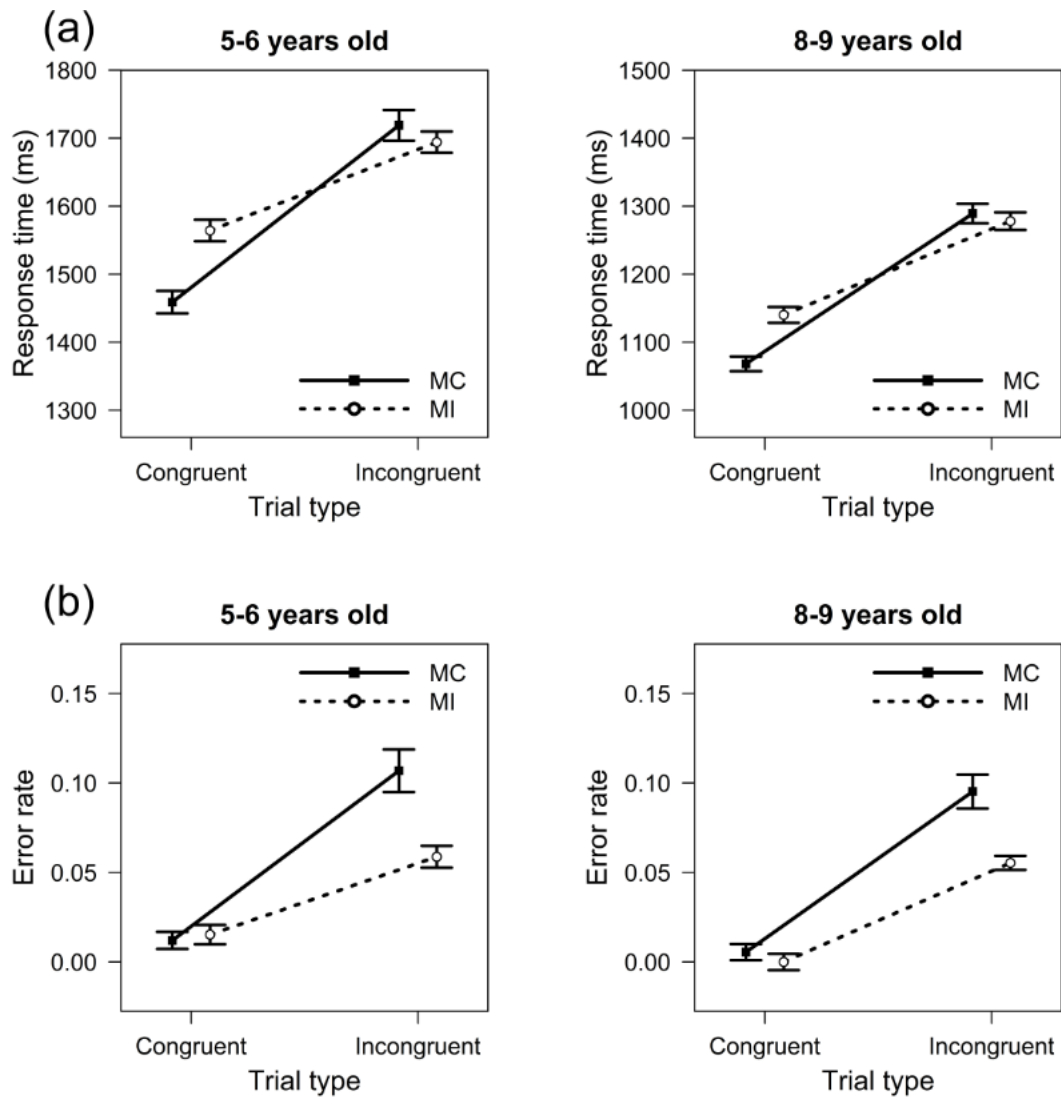


Figure 2. Data for Experiment 1, including (a) Response times and (b) Error rates as a function of age, proportion congruency and trial type. Error bars represent within-subjects standard errors of the mean (Morey, 2008). Note that the y-axis offset is different for the two age groups in panel (a).

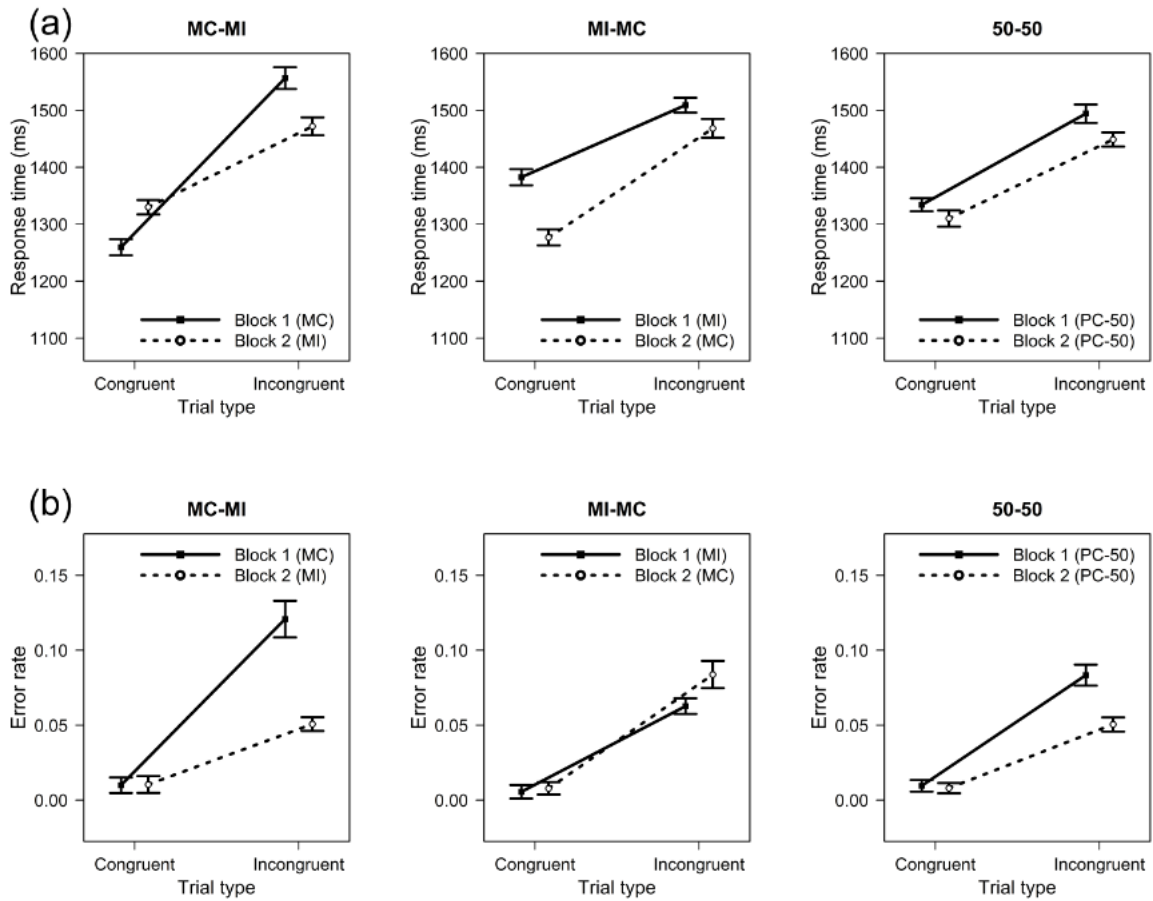
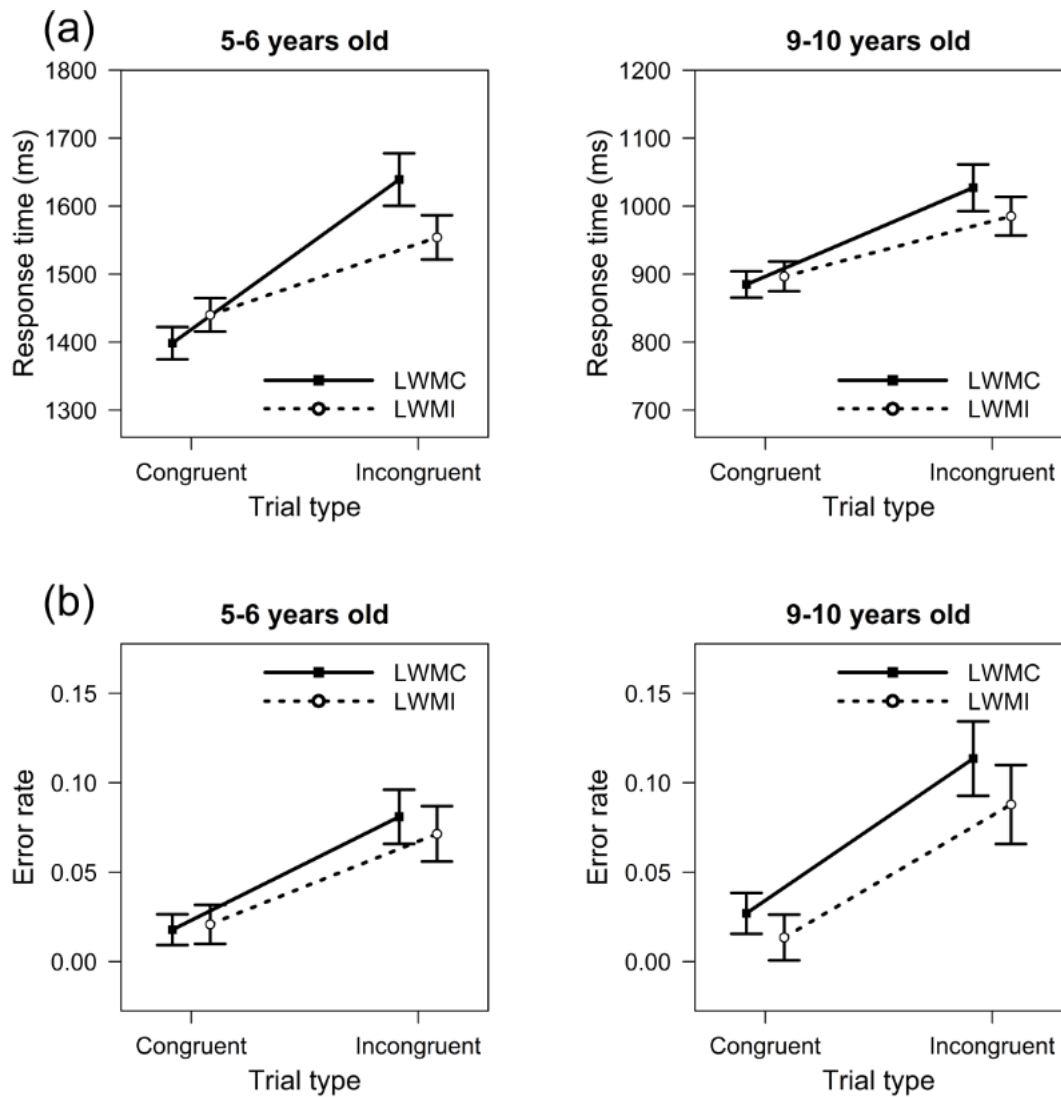
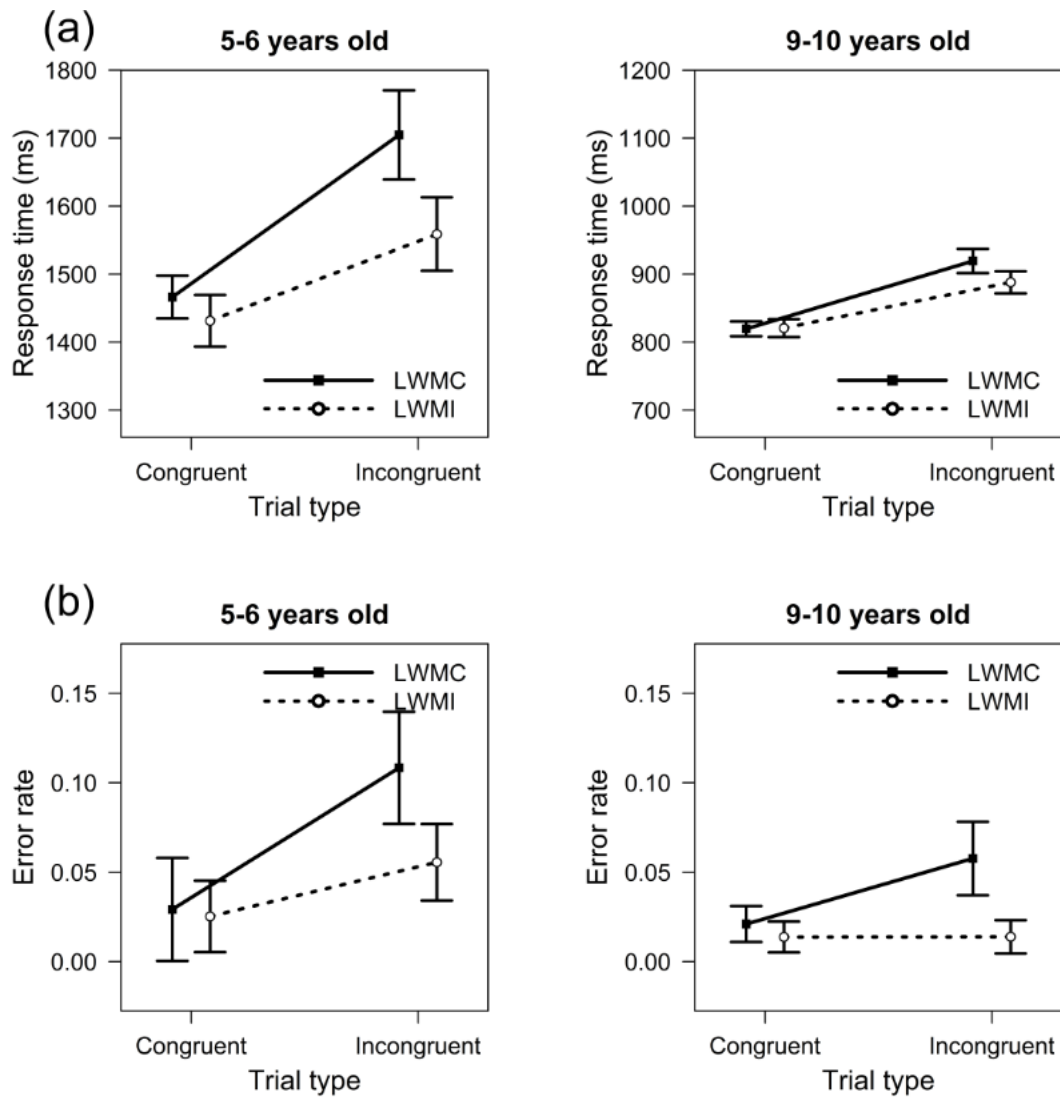


Figure 3. Data for Experiment 1, including (a) Response times and (b) Error rates as a function of experimental condition, task block and trial type. Note that solid lines and dashed lines represent the first and second block, which corresponds to different proportion congruencies in the different conditions. Error bars represent within-subjects standard errors of the mean (Morey, 2008).



*Figure 4.* Data for Experiment 2a, including (a) Response times and (b) Error rates as a function of age, task block and trial type. Error bars represent within-subjects standard errors of the mean (Morey, 2008). Note that the y-axis offset is different for the two age groups in panel (a).



*Figure 5.* Data for Experiment 2b, including (a) Response times and (b) Error rates as a function of age, task block and trial type. Error bars represent within-subjects standard errors of the mean (Morey, 2008). Note that the y-axis offset is different for the two age groups in panel (a).

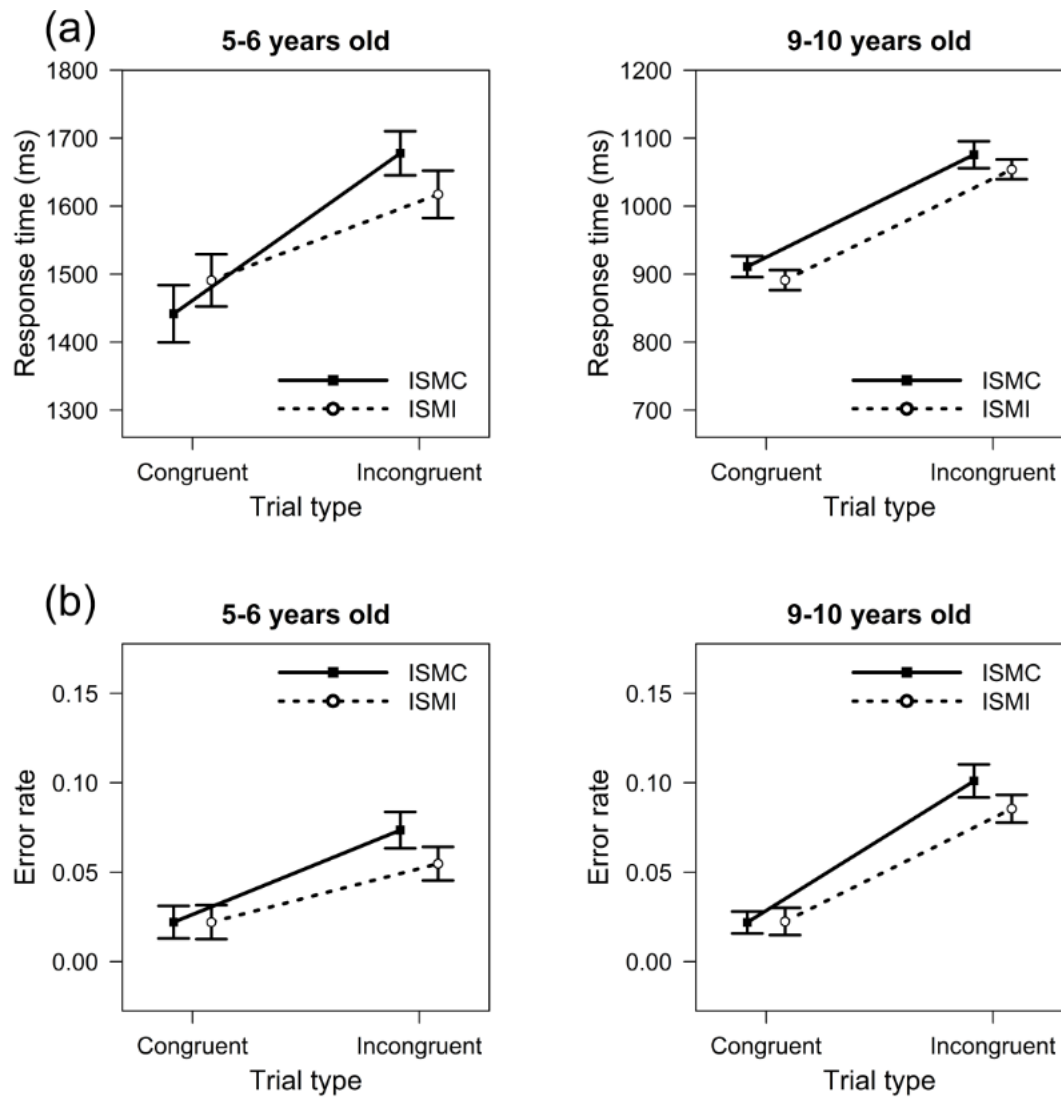
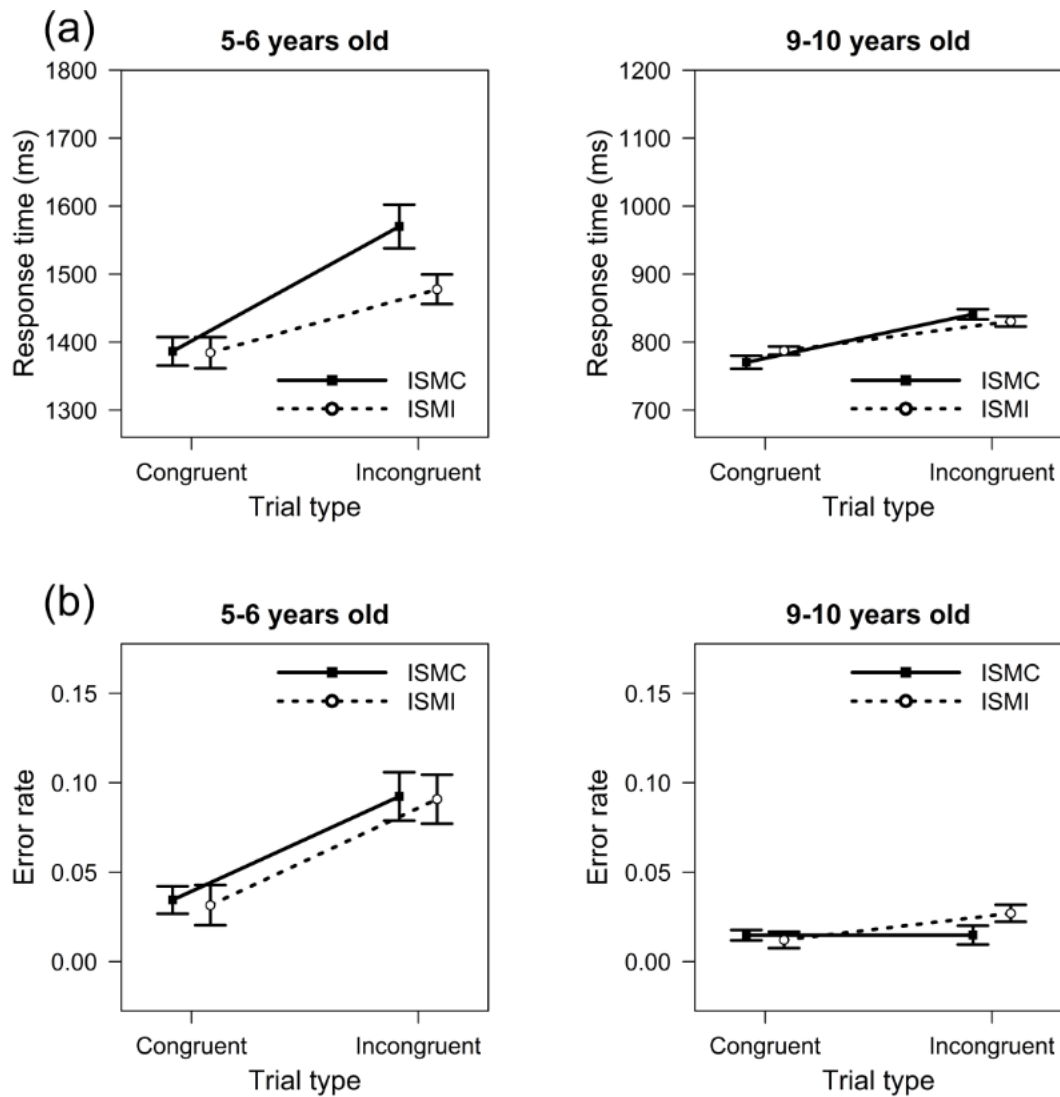


Figure 6. Data for Experiment 3a, including (a) Response times and (b) Error rates as a function of age, task block and trial type. Error bars represent within-subjects standard errors of the mean (Morey, 2008). Note that the y-axis offset is different for the two age groups in panel (a).



*Figure 7.* Data for Experiment 3b, including (a) Response times and (b) Error rates as a function of age, task block and trial type. Error bars represent within-subjects standard errors of the mean (Morey, 2008). Note that the y-axis offset is different for the two age groups in panel (a).