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Abstract

Cognitive control is often engaged in social contexts where actions are socially relevant. Yet, little is known about the immediate influence of the social context on childhood cognitive control. To examine whether competition or cooperation can enhance it, preschool and school-age children completed an AX Continuous Performance Task (AX-CPT) in competitive, cooperative, and neutral contexts. Children made fewer errors, responded faster, and engaged more cognitive effort, as shown by greater pupil dilation, in the competitive and cooperative social contexts, relative to the neutral context. Competition and cooperation yielded *greater* cognitive control engagement but did not change *how* control was engaged (reactively or proactively). Manipulating the social context can be a powerful tool to support cognitive control in childhood.

Key words: cognitive control, executive function, competition, cooperation, children.

Cognitive control, the goal-directed regulation of thoughts and actions, develops rapidly in early childhood, supporting greater autonomy and increasingly adaptive behavior with age. It is one of the best predictors of life success, including attention in the classroom and academic achievement in childhood, staying away from drug abuse and criminality in adolescence, and heath and income (e.g., Daly, Delaney, Egan, & Baumeister, 2015; Moffitt et al., 2011). Therefore, supporting cognitive control early in development has become a priority. Cognitive control training programs have yielded promising results (e.g., Diamond, 2012; Karbach & Unger, 2014) but training regimens are often lengthy, expensive, and difficult to implement. An alternative to training is to modify children's environment to support cognitive control transiently in situations where it is most needed (e.g., school activities). The social context is a salient environmental aspect that can easily be manipulated ecologically to optimize children's performance. Social factors such as socioeconomic status, parenting, and chronic stress have a long-term influence on cognitive control development (Moriguchi, 2014; Roskam, Stievenart, Meunier, & Noël, 2014). However, little is known about the immediate influence of the social context on children's cognitive control, even though children's actions are often performed in contexts where they are socially relevant and in interaction with other people. The present study investigates whether cognitive control can be enhanced through cooperation and competition in childhood.

One reason to suspect that cooperative contexts influence children's cognitive control is that, from early on, children show sensitivity (i.e., are not oblivious) to cooperation. Specifically, young children have been argued to have a drive for cooperation and engage in cooperative activities with adults or other children as early as their second year of life (Rekers, Haun, & Tomasello, 2011; Warneken &

Tomasello, 2006). For instance, infants and young children understand the basic principles of cooperation, such as the principle of reciprocity (Olson & Spelke, 2008), engage more spontaneously in cooperative than non-social activities (Warneken, Chen, & Tomasello, 2006), and regularly engage in cooperative play (Barbu, Cabanes, & Le Maner-Idrissi, 2011). They already take into account their partners' intentions and actively attempt to reengage partners who interrupt joint cooperative activities (Tomasello, Warneken, & Gra, 2012; Warneken et al., 2006; Warneken & Tomasello, 2007).

Importantly, beyond mere sensitivity, there is evidence that cooperation can actually influence children's performance in tasks tapping cognitive abilities such as theory of mind, categorization, and problem-solving (e.g., Garton & Pratt, 2001; Harris, Yuill, & Luckin, 2008; Rogoff, 1990, 1998). For instance, preschoolers persist longer on challenging tasks (e.g., difficult puzzles) in cooperative than non-cooperative contexts (Butler & Walton, 2013). To date the only study that examined the effect of cooperation on young children's cognitive control reported that the mere presence of a passive partner, who did not communicate with children, enhanced 3- and 4-year-old children's performance on a response inhibition task (Qu, 2011). In adults, cooperation yield better behavioral performance and modulate activity in prefrontal regions that support cognitive control (Cui, Bryant, & Reiss, 2012; de Bruijn, de Lange, von Cramon, & Ullsperger, 2009; Decety, Jackson, Sommerville, Chaminade, & Meltzoff, 2004; Liu, Saito, & Oi, 2015; Sebanz, Knoblich, Prinz, & Wascher, 2006).

As for cooperation, young children also show sensitivity to competition, displaying for instance greater pleasure when winning than losing against a competitor (Stipek et al., 1992), or engaging in less prosocial behaviors in competitive

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than non-social contexts (Pappert, Williams, & Moore, 2017). Competition can also have a direct influence on children's cognitive performance, as illustrated by school-age children's greater arithmetic performance after playing a math computer game against an opponent than with a partner or individually (Plass et al., 2013). Similarly, cognitive control training based on exergames (i.e., videogames involving physical exertion) induces even more beneficial short-term effects on older children's cognitive control in a competitive condition than in a cooperative or neutral condition (Staiano, Abraham, & Calvert, 2012). In adults, competition has similar effects as cooperation on cognitive control performance and related prefrontal cortex activity (Decety et al., 2004; Liu et al., 2015). Interestingly, unlike cooperation, competition seems to differentially affect boys than girls, with competition enhancing boys' performance in creativity or dexterity tasks, but yielding either no gain or even worse performance in girls, relative to individual contexts (Conti, Ann, & Picariello, 2001; Samak, 2013). However, it is unknown whether competition differentially affects cognitive control in boys and girls.

The beneficial effects of both competition and cooperation on cognitive control may be driven by enhanced motivation. Specifically, acting towards the same goal as a partner or competing with an opponent may increase awareness of the relevant task goal and willingness to adopt different perspectives and problem-solving methods that help children regulate their thoughts and actions (see Qu, 2011). Sharing a common goal with a partner may be intrinsically motivating (Decety et al., 2004), while competition has been repeatedly found to yield greater motivation, enjoyment, and task engagement (Cagiltay, Ozcelik, & Ozcelik, 2015; Conti et al., 2001; Nebel, Schneider, & Rey, 2016; Plass et al., 2013; Song, Kim, Tenzek, & Min, 2013). Both cooperation and competition may increase children's motivation to reach task goals

and thus lead to greater cognitive control engagement. In particular, cooperation and competition may constitute motivationally and emotionally significant contexts and thus may tap "hot" top-down control processes associated with ventromedial and orbitofrontal cortex (e.g., Lamm, Zelazo, & Lewis, 2006; Welsh & Peterson, 2014; Zelazo & Carlson, 2012). Joint recruitment of "hot" and "cool" control processes (associated with dorso- and ventrolateral prefrontal cortex) may lead to greater behavioral performance than neutral/individual contexts that solely tap "cool" control processes. Consistently, adults' cognitive control performance is associated with greater activity in orbitofrontal and medial prefrontal cortices in cooperative and competitive contexts, relative to a neutral context in which participants performed independently (Decety et al., 2004). Importantly, although competition is generally found to increase motivation, this effect may vary across individuals. For instance, less competitive individuals report lower motivation in competitive contexts than highly competitive individuals (Song et al., 2013). Indeed, competition may sometimes hinder performance if it induces additional stress and/or incite participants to monitor task-irrelevant information (Nebel et al., 2016).

An open question is whether any benefit of cooperation and competition on cognitive control would translate into only quantitative changes, due to engagement of more cognitive resources (or depleting cognitive resources), or also qualitative changes, that is, engagement of more mature modes of control, such as proactive control. According to the Dual Mechanisms of Control framework, two distinct control modes can be distinguished, reactive and proactive controls (Braver, 2012). Proactive control refers to the anticipation and preparation for a cognitively demanding task, by actively maintaining task-relevant information in advance of needing it, hence preventing interference before it occurs. By contrast, reactive

control refers to in-the-moment recruitment of control as a 'late-correction'
mechanism, after interference has already occurred, through bottom-up reactivation of
task-relevant information (Braver, 2012). Adults flexibly engage either form of
control as a function of task demands (e.g., Braver, Paxton, Locke, & Barch, 2009). In
contrast, preschoolers tend to engage reactive control exclusively, whereas from 6
years onwards children increasingly engage proactive control (Chatham, Frank, &
Munakata, 2009; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier, Martis,
Curran, & Munakata, 2015; Lucenet & Blaye, 2014). Intriguingly, although
preschoolers often do not spontaneously engage proactive control, they can actually
engage this control mode when it is encouraged (e.g., by making reactive control
more difficult; Chevalier et al., 2015), which leads to better performance (Chevalier &
Blaye, 2016; Chevalier et al., 2015). Thus, poor cognitive control in children may
stem in part from poor coordination of control modes (Chevalier, 2015). Greater
motivation due to cooperation and competition may lead children to better coordinate
control modes and more frequently engage proactive control, which is even more
plausible given that reward motivation fosters proactive control engagement in adults
(Braver et al., 2014; Chiew & Braver, 2013, 2016; Locke & Braver, 2008; Padmala &
Pessoa, 2011).

The present study examined (1) whether cooperation and competition can
enhance children's cognitive control performance, and (2) whether they induce purely
quantitative (i.e., children continue engaging the same control mode but they do so
more efficiently) or also qualitative (e.g., shift to more proactive control engagement)
changes. These questions were addressed in both preschoolers, who spontaneously
engage control reactively (despite being already capable of proactive control), and
school-age children, who have already started to transition to proactive control and

thus may be more likely to switch control modes as a function of the social context. Children completed the AX-CPT, a well-established measure of reactive and proactive control (Braver et al., 2009; Chatham et al., 2009; Chiew & Braver, 2013), in three conditions that varied in social context: a condition in which their score depended exclusively on their own performance (neutral condition), a condition in which they played with an adult partner and both parties would receive half of the team score (cooperative condition), and a condition in which they competed against the adult and *only* the better player (either the child or the adult opponent) would be able to collect their own points.

If cooperation and competition promote engagement of more mature cognitive control, they should be associated with a more pronounced proactive control response pattern, especially in school-age children who already show some proactive control engagement, relative to the neutral condition. If they yield quantitative benefits only, error rates and response times should be lower across the board in the cooperative and competitive conditions, but there should be no shift to a more proactive control response pattern. Finally, we also examined the influence of the social context on pupil dilation, a well-established marker of cognitive effort (Karatekin, 2007). If cooperation and competition yield greater cognitive control engagement children should show greater pupil dilation in these conditions than in the neutral condition.

Methods

Participants

Fifty-two children from 4 to 11 years of age participated in the study. Younger children ($N = 24$) were preschoolers ranging in age between 4;1 and 5;6 ($M = 60.1$ months, $SD = 4.9$ months, 11 females), while older children ($N = 28$) were school-age children ranging in age between 6;1 and 11;0 ($M = 99.8$ months, $SD = 19.3$ months,

10 females). An additional 6 children (2 preschool and 4 school-age children) were excluded because they did not complete the entire testing session. Most participants were Caucasian and from middle to high socioeconomic backgrounds. Parents gave informed consent before participating. Children received age-appropriate stickers and parents received a £10 voucher as compensation for their time and travel cost.

Procedure and Materials

Children were tested individually by two experimenters in the laboratory. One experimenter conveyed task instructions and monitored data acquisition while the other experimenter pretended to be playing the same computerized task as the child on a different computer (whose monitor was turned away from the child) and maintained a neutral attitude throughout the session. Each participant completed the AX-CPT in three conditions: neutral, cooperative, and competitive contexts (order counterbalanced across participants).

AX-Continuous Performance Task (AX-CPT). The AX-CPT was adapted from Chatham et al. (2009). The task was run using E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). There were four possible animal pictures: dog, cat, frog, and duck. Children were instructed to help the dog tell the cat that it was feeding time, pressing the "food bowl" button on a gamepad when the dog (A prime) was followed by the cat (X probe; AX trials), and the "x" button for all other combinations (i.e., dog-frog/AY trials, duck-cat/BX trials, duck-frog/BY trials), because the dog only wanted to help the cat and not other animals (Figure 1). On each trial, a prime (i.e., dog [A] or duck [B]) was presented for 500 ms, followed by a blank delay interval of 1200 ms, and the presentation of a probe (cat [X] or frog [Y]) along with two response images corresponding to the two response buttons (feeding bowl and x). The probe was presented until a response was entered or the time limit (calculated based

on the child's own response times—see below), whichever came first. Feedback was then presented for 1000 ms. After correct responses, the feedback screen showed two virtual candies if the response was fast, or one candy if the response was slower, accompanied by a short light tune. For incorrect or missing responses, a blank page appeared with a short crash sound. This feedback, provided after each trial, related to the child's own response only.

In each condition, children first completed four demonstration trials (which could be repeated if need be) in which the experimenter walked them through the task and made sure children understood task instructions. Demonstration trials were followed by 10 practice trials and five test blocks of 20 trials each. Practice trials were used to compute the two time limits used on all test trials: time limit for fast responses ($0.75 \times$ mean response time) below which children received two candies, and the time limit for a response to be registered ($1.5 \times$ mean response time). The time limits served to increase demands on cognitive control and encourage children to engage proactive control. Tailoring time limits to each child's own response times ensured that these limits were equally challenging to all participants, regardless of individual differences in processing and motor speeds. Each test block contained 14 AX trials, two AY, two BX, and two BY trials (random order).

Reactive and proactive control engagement was assessed by comparing BX and AY trials (Braver et al., 2009). Specifically, proactive control, that is, anticipation and preparation upon prime presentation to respond to the following probe (*I have just seen the dog so the cat should come next*), is generally associated with more errors and/or longer response times on AY trials (i.e., when the A prime was followed by a probe other than X) than BX trials. In contrast, reactive control, that is, prime retrieval from memory upon X probe detection (e.g*., here's the cat, did I just see the dog?*),

generally translates into more errors and slower response times on BX trials (where the X probe was indeed preceded by a prime other than A) than AY trials.

Social context manipulation. Each child completed three conditions (order counterbalanced). The social context manipulation was introduced after the practice phase of each condition. Children were told that for each game (condition), they would have an opportunity to win virtual candies in every round (i.e., block of trials) that they could later trade for a prize at the end of the session, and that accumulating more candies would result in a nicer prize. In all conditions, a confederate adult was present in the same room and pretended to play the same game on a different computer. The confederate was an adult rather than a child for practical reasons and to make sure that they would act consistently across all participants, which would have been difficult for a child to do. The conditions differed in how the confederate's role was introduced to the child and the rules for trading candies (score) later. In the cooperative condition, the confederate acted as a partner to the child and the child was told that she/he and the adult were now a team and their score would be half of the team's score. In the competitive condition, the confederate acted as an opponent and the child was told to try and outperform the opponent because *only* the player who accumulated most candies in each round (block of trials), either the child or the opponent, would be able to "collect" their own virtual candies to trade for a prize at the end. In the neutral condition, children were told that the confederate was also playing the game but the number of candies each person won depended entirely on their own performance. The confederate also pretended to play in this condition to ensure that any difference in children's performance across conditions could not relate to the mere presence of another adult in the same room but rather to the manipulation of the social context.

In all conditions, children could see how many candies they had won and how many candies the other player had won at the end of each test block, and were led to believe the other player received the same information. The number of candies displayed in the child's stack accurately reflected how well they did in that block, whereas the number of candies in the other player's stack was computed by adding or subtracting a set number (1, 2, or 3) of candies from the child's score (the exact same values were used across participants and conditions, but their order randomly varied across blocks). This way, the other player's score was equally often above or below the child's own score across blocks, and summed up to the exact same value as the child's score at the end of each condition. In the cooperative condition, the child was explicitly told each time that both she/he and the adult did well, and that they needed to keep playing to get even more candies. In the competitive condition, if the feedback showed a better score for the child, the child was told to keep trying to outperform the opponent. If the child had a lower score than the adult, she/he was told to try to outperform the opponent on the next block. In the neutral condition, the adult's performance was visually presented but not verbally highlighted; the child was simply encouraged to keep playing as well as they could to get even more candies.

Eye-tracking apparatus. An Eyelink 1000 eye-tracker (SR Research, Ottawa, Canada) was used to record pupil dilation with a sampling rate of 500 Hz between the onset of the cue and the provision of a response. The child's right eye was tracked. A 5-point calibration procedure was performed prior to each condition. Their track status was constantly monitored by the main experimenter during the task and checked before each new test block.

Data processing. Analysis of pupil dilation was limited to the interval from prime onset until 1200 ms after probe onset. Blinks were discarded. Gaze data for

correct trials were first averaged into consecutive 10-ms bins and smoothed using a

100-ms moving window, and then averaged for the entire window of interest. If

cooperation and competition lead to greater cognitive effort engagement overall, it

should be reflected in greater pupil dilation during the entire task. Thus, we used raw

pupil dilation (indexed as area in raw units), rather than percent change from a pre-

trial baseline, in order to capture tonic (sustained) effects of the social context on

pupil dilation (Chiew & Braver, 2013; Gilzenrat, Nieuwenhuis, Jepma, & Cohen,

2010).

Response times on correct trials were analyzed after removing values less than

200 ms (4.9%) and log transforming the remaining values to minimize skewness and

age-related baseline differences (Meiran, 1996). For the sake of clarity, reported

values were back-transformed. All the data were analyzed with linear mixed models

using the lme4 package in R (R Core Team, 2012). For all three indices (errors,

response times, pupil dilation), a mixed model was run on all trial types (AX, AY,

BX, BY) across the three conditions (neutral, cooperation, competition) for both age

groups (preschool, school-age)[1]. Given prior evidence for gender differences in

competition effects, gender (boys, girls) was also entered in the models[2] to explore its

effects. However, as the present study was not specifically designed to examine

gender differences and for the sake of clarity, gender is not included in Figure 2.

Descriptive statistics broken down by gender are provided in Supplemental Table 1.

Results

Error rates

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[1] The data were also analyzed with age as a continuous variable. The results showed
the exact same effects as when age was entered as a categorical variable.
[2] Whether or not gender was entered in the models, the effects of the other variables
were the same.

There was a significant effect of condition on error rates, $F(2, 566.9) = 7.06$, $p < .001$, pseudo $R^2 = .03$ (Figure 2, top). Overall, children made fewer errors in both the competitive (24.1%) and cooperative (26.9%) conditions than the neutral conditions (30.6%), $ps < .030$, with no difference between the cooperative and competitive condition, $p = .212$. In addition, the main effects of age group, $F(1, 51.1) = 22.88$, $p < .001$, pseudo $R^2 = .20$, and trial type, $F(3, 556.2) = 47.86$, $p < .001$, pseudo $R^2 = .33$, significantly interacted, $F(3, 556.2) = 46.19$, $p < .001$, pseudo $R^2 = .20$. Preschoolers made significantly more errors on BX trials (54.7%) than all other trials, including AY trials (34.8%), $ps < .001$, suggesting reactive control engagement. In contrast, school-age children made more errors on AY trials (43.6%) than all other trials, including BX trials (13.7%), $ps < .001$, suggesting proactive control engagement. None of the effects involving gender were significant, all $ps > .119$.

These effects along with the non-significant Condition × Trial Type and Condition × Trial Type × Age Group interactions suggest that competition and cooperation helped children engage control more effectively but did not affect the control mode that children engaged (i.e., always reactive control in preschoolers and always proactive control in school-age children).

Response times

There was a significant interaction between condition and age group on log-transformed response times, $F(2, 548) = 7.82$, $p < .001$, pseudo $R^2 = .03$ (Figure 2, middle). Unlike preschoolers whose response times did not vary across conditions, $ps > .646$, school-age children responded faster in the cooperative (459 ms) and the competitive conditions (485 ms) than the neutral condition (562 ms), $p = .001$ and $p = .019$, respectively). Response times did not differ significantly between the former two conditions, $p = .167$. In addition, gender significantly interacted with age group,

$F(1, 54.3) = 4.65$, $p = .035$, pseudo $R^2 < .01$, and condition, $F(2, 548) = 6.44$, $p =$ .001, pseudo $R^2 = .02$ (Supplemental Table 1). Relative to the neutral condition (722 ms), boys responded faster in the competitive condition (640 ms, $p = .007$) and marginally faster in the cooperative condition (649 ms, $p = .056$), with no significant difference between the two social conditions ($p = .442$). In contrast, girls took longer to respond in the competitive condition (812 ms) than in the neutral condition (762 ms, $p = .035$), while the cooperative condition (802 ms) did not differ from the others ($ps > .103$). Finally, the main effects of age group, $F(1, 54.3) = 64.18$, $p < .001$, pseudo $R^2 = .06$, and trial type, $F(3, 545.5) = 56.2$, $p < .001$, pseudo $R^2 = .21$, significantly interacted, $F(3, 545.6) = 8.17$, $p < .001$, pseudo $R^2 = .04$. Although both preschool and school-age children responded faster on BX (974 and 434 ms, respectively) than AY trials (1103 and 618 ms, respectively), $ps < .001$, the difference was greater in school-age children, suggesting more proactive control engagement in school-age children.

In brief, cooperation and competition yielded faster performance relative to the neutral context without modifying cognitive mode engagement, although the benefit on response times was limited to school-age children.

Pupil dilation

The main effect of condition on pupil dilation, $F(2, 514.6) = 7.87$, $p < .001$, pseudo $R^2 = .02$, was qualified by a significant interaction with age group, $F(2, 514.6) = 12.36$, $p < .001$, pseudo $R^2 = .04$ (Figure 2, bottom). In preschoolers, pupil dilation was greater in the competitive condition (2989 raw units) than in both cooperative (2896 raw units) and neutral (2885 raw units) conditions, $ps < .001$, with no difference between the latter two, $p = .736$. School-age children showed a different pattern with greater pupil dilation in the cooperative condition (2938 raw units) than

both competitive (2874 raw units, $p = .008$) and neutral (2869 raw units, $p < .001$) conditions, which did not differ from each other, $p = .282$.

In addition, there was a main effect of trial type, $F(3, 514.1) = 2.78$, $p = .041$, pseudo $R^2 = .01$, due to greater pupil dilation in BY trials (2927 raw units) than AX trials (2904 raw units, $p = .043$) and BX trials (2893 raw units, $p = .002$), but not AY trials (2909 raw units, $p = .102$). The main effect of gender, $F(1, 53.9) = 5.12$, $p = .028$, pseudo $R^2 < .01$, interacted with age group, $F(1, 53.9) = 5.09$, $p = .028$, pseudo $R^2 < .01$. Pupil dilation was greater in girls (3186 raw units) than boys (2689 raw units) at school age, $p = .001$, but not at preschool age, $p = .983$. Importantly, there was no significant interaction involving both gender and condition, all ps $> .127$.

These results suggest preschool children engaged greatest sustained cognitive effort when competing against an opponent, whereas school-age children likely engaged greatest cognitive effort during cooperation.

Discussion

The present study examined whether cooperation and competition influence children's cognitive control, as measured by the AX-CPT. Both preschool and school-age children made fewer errors and school-age children also responded faster in competitive and cooperative contexts than in a neutral context. In addition, preschool children engaged most cognitive effort in the competitive condition while school-age children engaged most cognitive effort in the cooperative condition. In contrast, there was no evidence for a qualitative change in control modes across conditions, that is, preschoolers and school-age children engaged control reactively and proactively, respectively, in all conditions but did it more efficiently when they competed against or cooperated with the other player than in the neutral context.

The present findings show that both competition and cooperation can

successfully support cognitive control in childhood, which is consistent with prior studies with adults and school-age children (Decety et al., 2004; Staiano et al. 2012) as well as with the beneficial effect of co-play at preschool age (Qu, 2011). Although the magnitude of the difference with the neutral condition is modest, the beneficial effect of cooperation and competition is especially noteworthy as it was observed through converging evidence from two (at preschool) or three (in older children) different indices: errors, response times, and pupil dilation. The lack of a response time difference in preschoolers may be due to the notoriously variable response times in early childhood.

Intriguingly, although both competition and cooperation yielded similar performance benefits in terms of response accuracy and response times (the latter in school-age children only), they influenced pupil dilation differently as a function of age, with preschoolers showing greatest pupil dilation during competition whereas school-age children showed greatest pupil dilation during cooperation. Preschoolers may have found the competitive context especially salient and motivating, which is consistent with prior findings suggesting that competition increases motivation in young children (e.g., Conti et al., 2001). Preschoolers may have found competition especially enjoyable and motivating, potentially because their immature metacognitive abilities, which often lead them to overestimate their performance (e.g., Flavell, Speer, Green, & August, 1981), lead them to overestimate their chance to outscore their opponent and to approach the competitive condition more optimistically than school-age children. School-age children, whose metacognitive abilities are more mature, may have found the cooperation even more motivating and enjoyable than competition. The role of metacognition should be investigated in future. Preschoolers may have found cooperation more motivating if it had involved

active rather than *passive* cooperation, that is, if they had interacted directly with their partner. Indeed, explaining one's thinking to a partner and joint elaboration on decision making are thought to contribute to the benefits of cooperation, and it is even more remarkable that cooperation influenced performance in the present study without these features of active cooperation. Similarly, cooperation could have had an even greater influence on young children if they had chosen their partner or played with a friend. Indeed, preschoolers' prosocial motivation has been found to be greater when they freely decide to help another person than when they are instructed to do so (Rapp, Engelmann, Herrmann, & Tomasello, 2017).

In the present study, competition was associated with faster responses in boys, but slower responses in girls, relative to the neutral condition. This asymmetrical effect between genders is consistent with prior findings suggesting that boys benefit more from competition than girls (Conti et al., 2001; Samak, 2013). In particular, competition may either have been less enjoyable to girls than boys or it may have led girls to monitor more information that is not directly task-relevant (e.g., stress), resulting in slower (but more accurate) responses in this condition. However, this is entirely speculative at this point and no condition × gender differences were observed for the other two indices. Therefore, these findings should be interpreted with caution, especially given that the present study was not designed specifically to examine gender differences and participants were not equally distributed between genders.

An important question is the mechanisms by which social contexts affects cognitive control performance in children. One possibility is that they increase the emotional and motivational aspects of the task, as suggested by greater emotional response than failing in a neutral condition in adults (Zeng, Zou, & Zhang, 2013). Therefore, in cooperative and competitive contexts, individuals may supplement

"cool" control processes engaged in the task by additionally recruiting "hot" cognitive control processes, resulting in greater performance. Consistently, pupil dilation data suggest children engaged more cognitive effort when cooperating or competing with an adult than when playing independently. These findings suggest neutral contexts may underestimate children's cognitive control abilities, as they do not necessarily encourage children to engage all their control resources. Indeed, cognitive control engagement relates to how children perceive and value cognitive effort (Chevalier, 2017).

We also examined whether cooperation and competition could influence cognitive control through another mechanism, metacognitive coordination of control modes. In particular, they could have helped children to engage proactive control, which is more efficient than reactive control on the AX-CPT (Braver et al., 2009; Chatham et al., 2009). However, we observed no evidence for a qualitative change in control modes across conditions. Preschoolers and school-age children engaged more control in the competitive and cooperative contexts, relative to the neutral context, but did not engage it in a qualitative different way across contexts: preschoolers always engaged control reactively whereas school-age children always engaged control more proactively. This lack of qualitative shift may be surprising given prior findings showing that (a) reward motivation fosters proactive control in adults (e.g., Chiew & Braver, 2016), and (b) environmental manipulations can successfully encourage preschoolers to engage control more proactively (Chevalier et al., 2015). However, unlike in that prior study, the social context manipulation did not target proactive control specifically (i.e., it did not make reactive control more difficult than proactive control). In other words, competition and cooperation may be incentives for children to engage *more* control, but not to optimize *how* control is engaged, which may

require more direct guidance in childhood.

The small sample size is a main limitation of the present study and, as previously stated, the effects of cooperation and competition on children's cognitive control, especially as a function of gender, should be further examined in future with larger sample sizes. Our within-subjects design may also be viewed as a main limitation, as it is possible that some participants might not have clearly distinguished the three conditions, hence potentially leading to carryover effects across conditions. Such carryover effects, however, would have worked towards masking any potential effect of the social context, and it is therefore even more noteworthy that we observed evidence for a beneficial effect of cooperation and competition on children's performance. Furthermore, our design had a number of strengths as it ensured that participants across all conditions were perfectly comparable, which is especially important for pupil dilation data. Additionally, the presence of the other player in the neutral condition rules out the possibility that the beneficial effects of cooperation and competition could reflect a generic social facilitation effect (i.e., due to the mere presence of that other player).

Finally, the present findings have important implications for supporting cognitive control outside of the laboratory. Simple modifications of the environment, through the introduction of a competitive or cooperative context, can be a viable alternative to training programs to support cognitive control during childhood. Training programs aim to permanently enhance cognitive control in children, running the risk to aversively impact the development of other cognitive skills, whose acquisition may benefit from immature executive functioning (e.g., language and creativity; Thompson-Schill, Ramscar, & Chrysikou, 2009). In contrast, environmental modifications of the social context can effectively support cognitive

control *transiently*, targeting situations where efficient cognitive control is particularly desirable, such as school or preschool activities. Importantly, we are *not* arguing for increased competitiveness in school settings, which may cause stress and other undesirable social consequences in the long run, but instead for ludic game-like situations in which cooperating with team members and competing against other teams may lead to greater enjoyment, motivation, and cognitive control engagement. Providing such contexts is potentially inexpensive and easy to implement in such settings. For all these reasons, modifications of the social context may be not only viable but also more desirable than training programs to support cognitive control in childhood.

References

Barbu, S., Cabanes, G., & Le Maner-Idrissi, G. (2011). Boys and girls on the playground: Sex differences in social development are not stable across early childhood. *PloS One*, *6*(1). http://doi.org/10.1371/journal.pone.0016407

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–13. http://doi.org/10.1016/j.tics.2011.12.010

Braver, T. S., Krug, M. K., Chiew, K. S., Kool, W., Westbrook, J. A., Clement, N. J., … Somerville, L. H. (2014). Mechanisms of motivation-cognition interaction: challenges and opportunities. *Cognitive, Affective & Behavioral Neuroscience*, *14*(2), 443–72. http://doi.org/10.3758/s13415-014-0300-0

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(18), 7351–6. http://doi.org/10.1073/pnas.0808187106

Butler, L. P., & Walton, G. M. (2013). The opportunity to collaborate increases preschoolers' motivation for challenging tasks. *Journal of Experimental Child Psychology*, *116*(4), 953–961. http://doi.org/10.1016/j.jecp.2013.06.007

Cagiltay, N. E., Ozcelik, E., & Ozcelik, N. S. (2015). The effect of competition on learning in games. *Computers & Education*, *87*, 35–41. http://doi.org/10.1016/j.compedu.2015.04.001

Chatham, C. H., Frank, M. J., & Munakata, Y. (2009). Pupillometric and behavioral markers of a developmental shift in the temporal dynamics of cognitive control. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(14), 5529–33. http://doi.org/10.1073/pnas.0810002106

Chevalier, N. (2015). The development of executive function: Toward more optimal coordination of control with age. *Child Development Perspectives*, *9*(4), 239–244. http://doi.org/10.1111/cdep.12138

Chevalier, N. (2017). Willing to think hard? The subjective value of cognitive effort in children. *Child Development*, *0*(0), 1–13. http://doi.org/10.1111/cdev.12805

Chevalier, N., & Blaye, A. (2016). Metacognitive monitoring of executive control engagement during childhood. *Child Development*, *87*(4), 1264–1276. http://doi.org/10.1111/cdev.12537

Chevalier, N., James, T. D., Wiebe, S. a, Nelson, J. M., & Espy, K. A. (2014). Contribution of reactive and proactive control to children's working memory performance: Insight from item recall durations in response sequence planning. *Developmental Psychology*, *50*(7), 1999–2008. http://doi.org/10.1037/a0036644

Chevalier, N., Martis, S. B., Curran, T., & Munakata, Y. (2015). Metacognitive processes in executive control development: The case of reactive and proactive control. *Journal of Cognitive Neuroscience*, *27*(6), 1125–1136. http://doi.org/10.1162/jocn

Chiew, K. S., & Braver, T. S. (2013). Temporal dynamics of motivation-cognitive control interactions revealed by high-resolution pupillometry. *Frontiers in Psychology*, *4*(January), 15. http://doi.org/10.3389/fpsyg.2013.00015

Chiew, K. S., & Braver, T. S. (2016). Reward Favors the Prepared : Incentive and Task-Informative Cues Interact to Enhance Attentional Control, *42*(1), 52–66.

Conti, R., Ann, M., & Picariello, M. L. (2001). The impact of competition on intrinsic motivation and creativity : considering gender , gender segregation and gender role orientation. *Personality and Individual Differences*, *30*, 1273–1289.

Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals

increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage*, *59*(3), 2430–2437. http://doi.org/10.1016/j.neuroimage.2011.09.003

Daly, M., Delaney, L., Egan, M., & Baumeister, R. F. (2015). Childhood self-control and unemployment throughout the life span: Evidence from two British cohort studies. *Psychological Science*. http://doi.org/10.1177/0956797615569001

de Bruijn, E. R. a, de Lange, F. P., von Cramon, D. Y., & Ullsperger, M. (2009). When errors are rewarding. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *29*(39), 12183–6. http://doi.org/10.1523/JNEUROSCI.1751-09.2009

Decety, J., Jackson, P. L., Sommerville, J. a, Chaminade, T., & Meltzoff, A. N. (2004). The neural bases of cooperation and competition: an fMRI investigation. *NeuroImage*, *23*(2), 744–51. http://doi.org/10.1016/j.neuroimage.2004.05.025

Diamond, a. (2012). Activities and Programs That Improve Children's Executive Functions. *Current Directions in Psychological Science*, *21*(5), 335–341. http://doi.org/10.1177/0963721412453722

Flavell, J. H., Speer, J. R., Green, F. L., & August, D. L. (1981). The development of comprehension monitoring and knowledge about communication. *Monographs of the Society for Research in Child Development*, *46*, 1–65.

Garton, A. F., & Pratt, C. (2001). Peer assistance in children ' s problem solving. *British Journal of Developmental Psychology*, *19*, 307–318.

Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cognitive Affective & Behavioral Neuroscience*, *10*(2), 252–269. http://doi.org/10.3758/CABN.10.2.252

Harris, A., Yuill, N., & Luckin, R. (2008). The influence of context-specific and dispositional achievement goals on children ' s paired collaborative interaction. *British Journal of Educational Psychology*, *78*, 355–374. http://doi.org/10.1348/000709907X267067

Karatekin, C. (2007). Eye tracking studies of normative and atypical development. *Developmental Review*, *27*, 283–348. http://doi.org/10.1016/j.dr.2007.06.006

Karbach, J., & Unger, K. (2014). Executive control training from middle childhood to adolescence. *Frontiers in Psychology*, *5*(May), 390. http://doi.org/10.3389/fpsyg.2014.00390

Lamm, C., Zelazo, P. D., & Lewis, M. D. (2006). Neural correlates of cognitive control in childhood and adolescence: disentangling the contributions of age and executive function. *Neuropsychologia*, *44*(11), 2139–48. http://doi.org/10.1016/j.neuropsychologia.2005.10.013

Liu, T., Saito, H., & Oi, M. (2015). Role of the right inferior frontal gyrus in turn-based cooperation and competition: A near-infrared spectroscopy study. *Brain and Cognition*, *99*, 17–23. http://doi.org/10.1016/j.bandc.2015.07.001

Locke, H. S., & Braver, T. (2008). Motivational influences on cognitive control: Behavior, brain activation, and individual differences. *Cognitive Affective & Behavioral Neuroscience*, *8*(1), 99–112. http://doi.org/10.3758/CABN.8.1.99

Lucenet, J., & Blaye, A. (2014). Age-related changes in the temporal dynamics of executive control: a study in 5- and 6-year-old children. *Frontiers in Psychology*, *5*(July), 1–11. http://doi.org/10.3389/fpsyg.2014.00831

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1423–1442. http://doi.org/10.1037/0278-7393.22.6.1423

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., … Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2693–8. http://doi.org/10.1073/pnas.1010076108

Moriguchi, Y. (2014). The early development of executive function and its relation to social interaction: a brief review. *Frontiers in Psychology*, *5*(April), 388. http://doi.org/10.3389/fpsyg.2014.00388

Nebel, S., Schneider, S., & Rey, G. D. (2016). Computers in Human Behavior From duels to classroom competition : Social competition and learning in educational videogames within different group sizes. *Computers in Human Behavior*, *55*, 384–398. http://doi.org/10.1016/j.chb.2015.09.035

Olson, K. R., & Spelke, E. S. (2008). Foundations of cooperation in young children. *Cognition*, *108*, 222–231. http://doi.org/10.1016/j.cognition.2007.12.003

Padmala, S., & Pessoa, L. (2011). Reward reduces conflict by enhancing attentional control and biasing visual cortical processing. *Journal of Cognitive Neuroscience*, *23*(11), 3419–3432.

Pappert, A., Williams, A., & Moore, C. (2017). The Influence of Competition on Resource Allocation in Preschool Children. *Social Development*, *26*(2), 367–381. http://doi.org/10.1111/sode.12202

Plass, J. L., Keefe, P. A. O., Homer, B. D., Case, J., Hayward, E. O., & Stein, M. (2013). The Impact of Individual , Competitive , and Collaborative Mathematics Game Play on Learning , Performance , and Motivation. *Journal of Educational Psychology*, *105*(4), 1050–1066. http://doi.org/10.1037/a0032688

Qu, L. (2011). Two is better than one, but mine is better than ours: Preschoolers'

executive function during co-play. *Journal of Experimental Child Psychology*, *108*, 549–566. http://doi.org/10.1016/j.jecp.2010.08.010

Rapp, D. J., Engelmann, J. M., Herrmann, E., & Tomasello, M. (2017). Journal of Experimental Child The impact of choice on young children ' s prosocial motivation, 1–10. http://doi.org/10.1016/j.jecp.2017.01.004

Rekers, Y., Haun, D. B. M., & Tomasello, M. (2011). Report Children , but Not Chimpanzees , Prefer to Collaborate. *Current Biology*, *21*(20), 1756–1758. http://doi.org/10.1016/j.cub.2011.08.066

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context*. Oxford University Press. New York, NY, US.

Rogoff, B. (1998). *Cognition as a collaborative process. Handbook of child psychology: Volume 2: Cognition, perception, and language*. (pp. 679-744) Hoboken, NJ, US: John Wiley & Sons Inc, xxvi, 1030 pp.

Roskam, I., Stievenart, M., Meunier, J., & Noël, M. (2014). Journal of Experimental Child The development of children ' s inhibition : Does parenting matter ? *Journal of Experimental Child Psychology*, *122*, 166–182. http://doi.org/10.1016/j.jecp.2014.01.003

Samak, A. C. (2013). Journal of Economic Behavior & Organization Is there a gender gap in preschoolers ' competitiveness ? An experiment in the U . S &. *Journal of Economic Behavior and Organization*, *92*, 22–31. http://doi.org/10.1016/j.jebo.2013.04.014

Sebanz, N., Knoblich, G., Prinz, W., & Wascher, E. (2006). Twin peaks: an ERP study of action planning and control in co-acting individuals. *Journal of Cognitive Neuroscience*, *18*(5), 859–70. http://doi.org/10.1162/jocn.2006.18.5.859

Song, H., Kim, J., Tenzek, K. E., & Min, K. (2013). Com puters in Human Behavior The effects of competition and competitiveness upon intrinsic motivation in exergames. *Computers in Human Behavior*, *29*(4), 1702–1708. http://doi.org/10.1016/j.chb.2013.01.042

Staiano, A. E., Abraham, A. a, & Calvert, S. L. (2012). Competitive versus cooperative exergame play for African American adolescents' executive function skills: Short-term effects in a long-term training intervention. *Developmental Psychology*, *48*(2), 337–42. http://doi.org/10.1037/a0026938

Stipek, D., Recchia, S., & McClintic, S. (1992). Self-evaluation in young children. *Monographs of the Society for Research in Child Development, 57*, Serial No. 226.

Thompson-Schill, S. L., Ramscar, M., & Chrysikou, E. G. (2009). Cognition without control: When a little frontal lobe goes a long way. *Current Directions in Psychological Science : A Journal of the American Psychological Society*, *18*(5), 259–263. http://doi.org/10.1111/j.1467-8721.2009.01648.x

Tomasello, M., Warneken, F., & Gra, M. (2012). Collaborative partner or social tool ? New evidence for young children's understanding of joint intentions in collaborative activities. *Developmental Science*, *1*, 54–61. http://doi.org/10.1111/j.1467-7687.2011.01107.x

Warneken, F., Chen, F., & Tomasello, M. (2006). Cooperative activities in young children and chimpanzees. *Child Development*, *77*(3), 640–663.

Warneken, F., & Tomasello, M. (2006). Altruistic Helping in Human Infants and Young Chimpanzees. *Science*, *311*(March), 1301–1304.

Warneken, F., & Tomasello, M. (2007). Helping and Cooperation at 14 Months of Age. *Infancy*, *11*(3), 271–294.

Welsh, M., & Peterson, E. (2014). Issues in the Conceptualization and Assessment of

    Hot Executive Functions in Childhood. *Journal of the International*

    Neuropsychological Society, *20*, 152–156.

    http://doi.org/10.1017/S1355617713001379

Zelazo, P. D., & Carlson, S. M. (2012). Hot and Cool Executive Function in

    Childhood and Adolescence: Development and Plasticity. *Child Development*

    Perspectives, *6*(4), n/a-n/a. http://doi.org/10.1111/j.1750-8606.2012.00246.x

Zeng, J., Zou, Y., & Zhang, Q. (2013). Social competition factor influences the neural

    response to rewards: an ERP study. *Brain Research*, *1501*, 12–20.

    http://doi.org/10.1016/j.brainres.2013.01.030
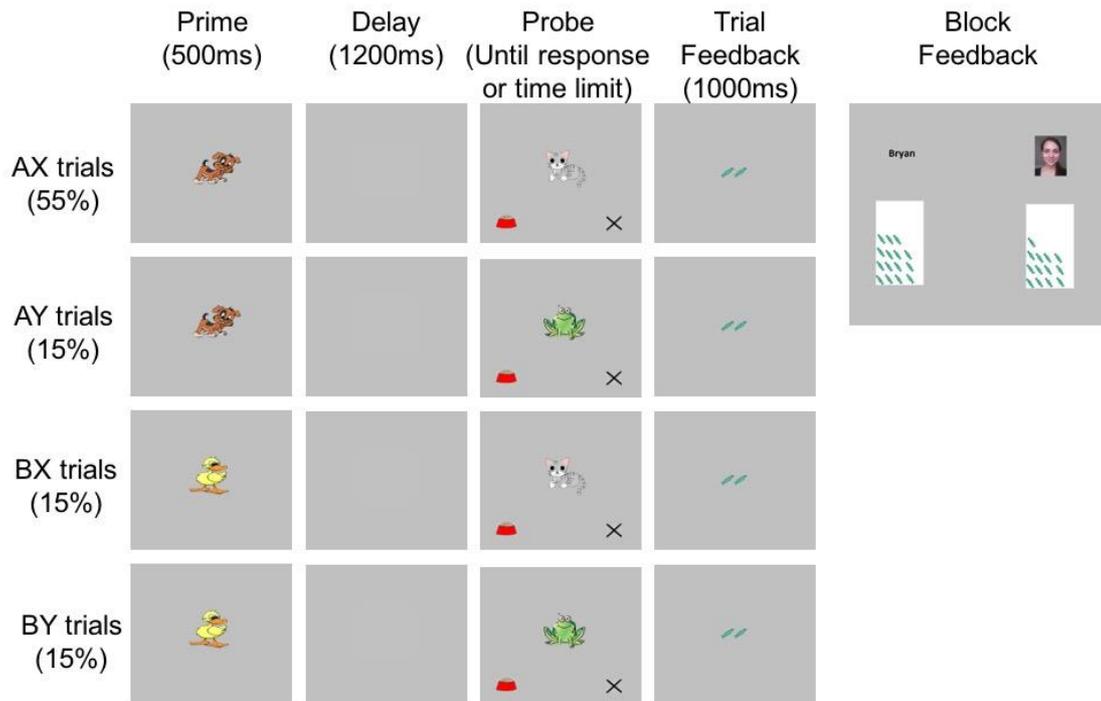
Figure 1. Illustration of each trial type and example of block feedback used in the AX-CPT. The block feedback screen was shown after each test block. The left-hand column shows the participant's name and reward, while the right-hand column shows the other player's picture and reward.
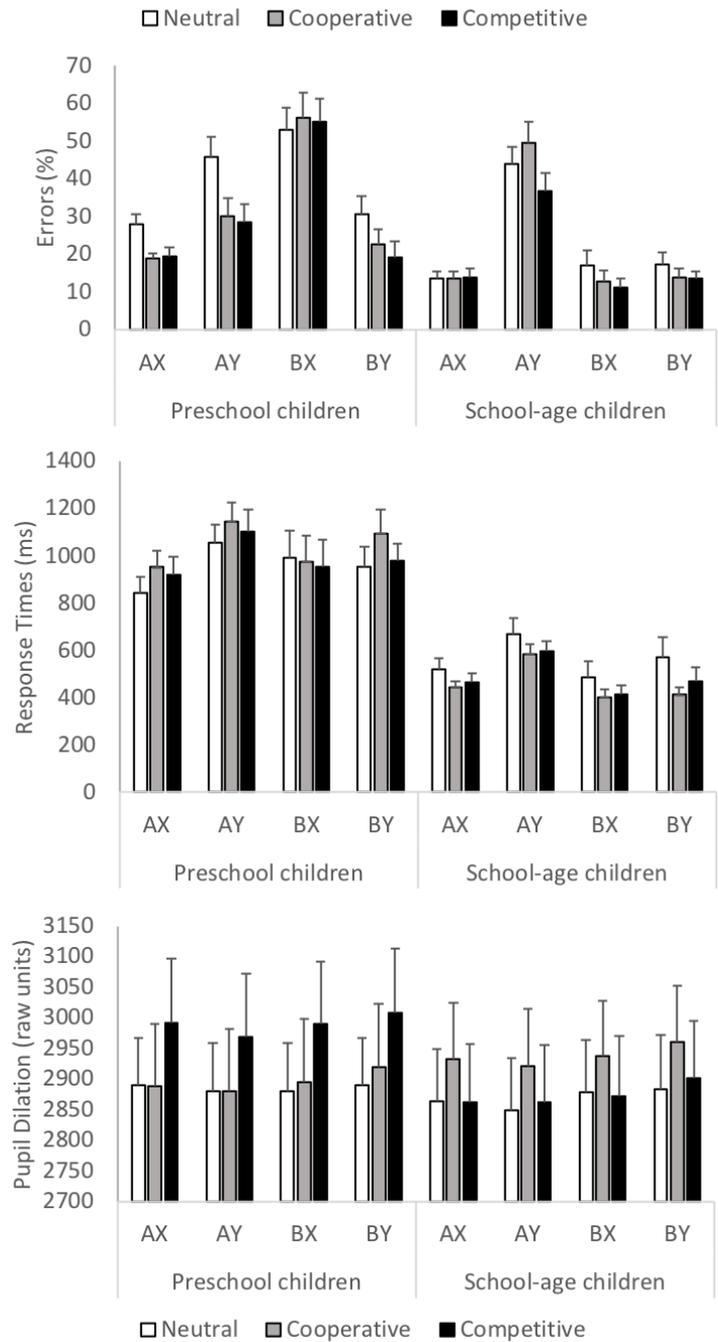
Figure 2. Errors (top panel), response times (middle panel), and pupil dilation (bottom panel) on AX-CPT as a function of condition, trial type, and age group. Error bars indicate the standard errors. Both age groups responded more accurately and school-age children also responded faster in the cooperative and competitive conditions, relative to the neutral conditions. Pupil dilation was greatest in the competitive condition in preschoolers and in the cooperative condition in school-age children.

Supplemental Table 1. *Mean (standard deviation) error rates (%), response times (milliseconds) and pupil dilation (raw units) as a function of age group, gender, trial type and condition.*

Measure	Age Group	Gender	Condition & Trial Type											
			Neutral				Cooperative				Competitive			
			AX	AY	BX	BY	AX	AY	BX	BY	AX	AY	BX	BY
Errors	Preschool Children	Girls	29.4 (11.6)	39 (29.7)	54.2 (26.3)	28.7 (24.2)	18.2 (8.5)	23.5 (21.6)	53.3 (31.1)	18.8 (16)	20.3 (15.6)	19.9 (13)	53.6 (34.4)	16.3 (11.6)
		Boys	27 (14.8)	51.3 (24.1)	52.2 (30.8)	32.4 (24.7)	19.3 (5.4)	35.6 (24.8)	58.7 (35.9)	26 (21.1)	18.6 (9.2)	35.2 (28.6)	56.2 (30)	21.4 (26.6)
	School-Age Children	Girls	9.1 (7.2)	43.9 (20.8)	16.1 (19.8)	17.2 (15.7)	10.3 (4)	50 (28.9)	12.8 (14.3)	11.7 (6.4)	10.3 (12.6)	27.8 (24.6)	13.3 (14.8)	11.1 (11.1)
		Boys	16.7 (11)	44.1 (27)	17.6 (24.7)	17.2 (19.5)	15.6 (13.7)	49.5 (31.5)	13 (17.7)	15.4 (16)	16.4 (13.6)	43 (25.9)	10 (12.2)	15.2 (11.2)
Response Times	Preschool Children	Girls	969 (381)	1189 (369)	1211 (597)	1072 (418)	1075 (415)	1246 (424)	1185 (609)	1314 (640)	1107 (434)	1341 (544)	1216 (592)	1139 (343)
		Boys	748 (255)	953 (365)	820 (504)	858 (424)	848 (238)	1062 (345)	767 (326)	908 (247)	776 (248)	919 (260)	736 (373)	855 (322)
	School-Age Children	Girls	441 (85)	572 (79)	388 (86)	443 (115)	409 (95)	537 (125)	372 (99)	390 (100)	434 (77)	583 (106)	394 (124)	443 (120)
		Boys	570 (328)	732 (492)	553 (469)	665 (557)	464 (184)	616 (250)	422 (212)	427 (221)	486 (253)	604 (288)	426 (265)	490 (414)
Pupil Dilation	Preschool Children	Girls	2811 (331)	2801 (335)	2806 (333)	2800 (334)	2954 (587)	2927 (575)	2968 (581)	2972 (586)	3005 (615)	2995 (619)	2993 (605)	3029 (622)
		Boys	2951 (372)	2940 (377)	2936 (391)	2956 (368)	2829 (348)	2839 (367)	2830 (356)	2873 (369)	2984 (443)	2951 (421)	2987 (428)	2988 (440)
	School-Age Children	Girls	3142 (513)	3130 (500)	3155 (497)	3172 (531)	3256 (609)	3245 (609)	3247 (614)	3268 (607)	3130 (639)	3133 (633)	3161 (658)	3171 (631)
		Boys	2654 (274)	2637 (272)	2672 (277)	2668 (274)	2711 (299)	2700 (306)	2725 (289)	2751 (308)	2673 (300)	2671 (286)	2667 (302)	2711 (296)