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How do distracting events influence children's arithmetic performance?

Patrick Lemaire [a,*], Kerry Lee [b]

[a] Laboratoire de psychologie cognitive (LPC), Aix-Marseille Université, and Centre national de la recherche scientifique (CNRS), 13331 Marseille, France
[b] Department of Early Childhood Education, The Education University of Hong Kong, Tai Po, Hong Kong Special Administrative Region

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ABSTRACT

To understand how distraction influences children's arithmetic performance, we examined effects of irrelevant sounds on children's performance while they solve arithmetic problems. Third and fifth graders were asked to verify true/false, one-digit addition problems (e.g., 9 + 4 = 12. True? False?) under silence and sound conditions. The sounds began when the problems started to appear on the screen (Experiment 1; $N = 76$) or slightly after (Experiment 2; $N = 92$) and continued until participants responded. The results showed that (a) children solved arithmetic problems more quickly in the sound condition than in the silence condition when the sounds started with problem display (phasic arousal effects); (b) children were slower on the arithmetic problem verification task when the sounds was played slightly after the problems started to appear on the screen (distraction effects); (c) phasic arousal effects were found only in third graders, whereas distraction effects were found in both grades, although their magnitudes were smaller in fifth graders; (d) distraction effects increased with increasing latencies in third graders but did not change across the entire latency distribution in fifth graders; and (e) distraction effects on current trials were smaller after sound trials than after silence trials in both age groups (sequential modulations of distraction effects). These findings have important implications for furthering our understanding of effects of irrelevant sounds on arithmetic performance as well as cognitive processes involved in children's arithmetic.

* Corresponding author.
E-mail address: patrick.lemaire@univ-amu.fr (P. Lemaire).

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Introduction

The goal of the current study was to examine how distraction influences children's arithmetic performance and how this influence changes with children's age. Although distraction has been investigated in a number of cognitive domains and tasks, surprisingly little research has examined effects of distraction in arithmetic. As a consequence, we ignore how distracting events influence arithmetic performance in children and how this influence differs in younger and older elementary-school children. Determining how distracting events affect children's performance is important both theoretically and practically. Theoretically, determining how arithmetic performance is affected by distracting events speaks to the role of attention in arithmetic problem solving and how age-related changes in both attention and arithmetic fluency contribute to increases in children's arithmetic proficiency. From a more practical perspective, understanding the mechanisms underlying the effects of distraction on children's arithmetic performance is important to help children resist deleterious effects of distracting events in the context of classrooms and other environments that can be noisy places with chatter among classmates and different activities occurring concurrently or where street noise and noise from adjoining classrooms can be heard. We first briefly review previous relevant findings on children's arithmetic. We then review how effects of distracting events on cognitive performance is investigated and main relevant findings regarding effects of distraction before we describe the logic of the current study.

Previous findings in arithmetic

The goal of the psychology of arithmetic is to determine how people solve arithmetic problems as simple as 3 + 4 and 8 × 7 or more complex problems like 123 + 879 and 43 × 87 and what factors affect participants' performance. Developmental research aims at understanding how arithmetic performance changes with children's age, understanding how effects of factors on participants' performance change with children's age, and uncovering mechanisms responsible for these age-related changes. Two types of tasks have been used to pursue these goals, namely production and verification tasks. In production tasks, participants are given problems (e.g., 8 × 7 =?; 456 + 348 =?) and need to find solutions. In verification tasks, participants are given arithmetic equations (e.g., 8 × 4 = 32; 23 × 4 = 93) and need to say whether these equations are true or false. In both types of tasks, participants' performance is influenced by a variety of parameters (for overviews, see Cohen Kadosh & Dowker, 2015; Knops, 2020). These include participants' characteristics (e.g., their age, school level, culture, working memory, and executive control resources), stimulus features (e.g., problem size, odd/even status of operands), strategies (e.g., retrieval, counting), and situation or task environment (e.g., speed–accuracy pressures, response deadlines). For example, participants are faster when they solve smaller problems like 3 × 4 than when they solve larger problems like 8 × 7 (e.g., Zbrodoff, 1995), when they verify true problems like 8 + 4 = 12 than when they verify false problems like 8 + 4 = 13 (e.g., Fabre & Lemaire, 2019), on digitally presented problems (e.g., 8 + 4) versus verbally presented problems (e.g., eight plus four) (e.g. Mauro et al., 2003), when problems are presented in the auditory format relative to the visual format (LeFevre et al., 2001), when participants are tested under speed pressures or response deadlines (e.g., Campbell & Austin, 2002; Lemaire et al., 2004), and when participants have more working memory resources (e.g., Lee & Bull, 2016).

Children's arithmetic performance improves as children grow older and effects of determiners of arithmetic performance change with children's age (for an overview, see Geary, 1994; Gilmore et al., 2018). Not only do children become faster and more accurate, but they are also less influenced by some factors like problem characteristics and available attentional resources. For example, as children grow older, differences in performance tend to decrease between large and small problems or between true and false problems in arithmetic problem verification tasks (Geary, 1996; Hamann & Ashcraft, 1985; Koshmider & Ashcraft, 1991; Lemaire & Lecacheur, 2011; Lemaire & Siegler, 1995). This occurs because the cognitive mechanisms processing such problem features become more automatic with increased arithmetic fluency.

Another set of previous findings is relevant for investigating the influence of distraction in children's arithmetic. Several studies documented the role of executive control in mathematical cognition in general and arithmetic in particular (e.g., Bull et al., 1999; Bull & Lee, 2014; Bull & Scerif, 2001; Cragg & Gilmore, 2014). These studies showed that executive control processes play an important role when children accomplish a variety of math tasks. Different executive processes have been studied in arithmetic, including working memory (Imbo & Vandierendonck, 2007; Lee & Bull, 2016; Lemaire et al., 1996; Peng et al., 2016), flexibility (e.g., Hodzik & Lemaire, 2011; Lemaire & Lecacheur, 2010), updating (Hammerstein et al., 2019, in press), and inhibition (e.g., Khng & Lee, 2009; Lemaire et al., 1994). For example, Lemaire et al. (1994) found that inhibition enabled both adults and children to disregard erroneous answer candidates when retrieving arithmetic facts (e.g., inhibiting 28 when retrieving the correct product of 4×6). As another example, Lemaire and Lecacheur (2010) found that flexibility enabled children to select the better strategy when finding estimates of two two-digit addition problems. In addition, using a dual-task paradigm, Lee et al. (2009) found that executive suppression resulted in a larger reduction in word problem-solving accuracy than did articulatory suppression. Finally, Barrouillet and Lépine (2005) found that children with high memory spans tended to use retrieval more often than children with low memory spans to retrieve correct sums of one-digit addition problems (e.g., 8 + 4). Thus, executive control processes are important in arithmetic and arithmetic development. These processes may be crucial when children accomplish arithmetic problem-solving tasks while trying to not be disturbed by noisy environments such as -in classrooms, with chatting among classmates and different activities occurring concurrently or noise from outside. The goal of this study was to examine effects of distracting events on arithmetic performance, and age-related changes in this distraction. To achieve these ends, we tested the effects of distraction on arithmetic via examining how irrelevant sounds influenced performance while children accomplished arithmetic problem verification tasks. We based the current experiments on studies testing effects of irrelevant sounds on cognitive performance outside the domain of arithmetic.

Previous findings on effects of irrelevant sounds

Previous studies in the general literature on attention and attention development found that unexpected task-irrelevant sounds have two effects on participants' performance: arousal and distraction effects. First, unexpected irrelevant sounds induce a burst of phasic arousal that results in behavioral benefits such as reduced reaction times (e.g., Bidet-Caulet et al., 2015; Max et al., 2015; Wetzel et al., 2012). Such a burst of phasic arousal triggered by salient sounds would be mediated by the norepinephrine system, and it results in a transient and nonspecific state of readiness to respond to any upcoming stimulus or to accomplish a task (Aston-Jones & Cohen, 2005; Corbetta et al., 2008). Second, unexpected irrelevant sounds can also capture our attention and trigger distraction, which results in behavioral costs or impaired performance on a target cognitive task. Distraction leads to poorer performance via the reactive allocation of attention and resources to an event or stimulus external to the cognitive task, followed by a reallocation of attention and resources toward the task (e.g., Bidet-Caulet et al., 2015; ElShafei et al., 2020b; Escera et al., 2000).

Whether distracting sounds generate facilitation phasic arousal and/or deleterious distraction effects on cognitive performance depends on several factors such as task demands (e.g., SanMiguel et al., 2010) and the sound–target delay (e.g. Bidet-Caulet et al., 2015). For example, in a series of experiments, Bidet-Caudet and collaborators tested arousal and distraction effects in the Competitive Attention Task. Participants needed to detect a target sound and indicate whether the sound was played in the left or right ear (Bidet-Caulet et al., 2015; Masson & Bidet-Caulet, 2019; ElShafei et al., 2020a, 2020b). Participants were faster at detecting a target sound in an early-distractor condition (i.e., when distracting sounds were played in the 350- to 650-ms range before the target sounds) and decreased their speed detection in a late-distractor condition (i.e., when distracting sounds were played in the 50- to 350-ms range before the target sounds). The authors proposed that early sound induced a burst of phasic arousal, which led them to increase their speed at detecting target sounds, and that later sounds captured participants' attention and distracted them from the main target sound detection, which led them to decrease their speed detection.

Both facilitation and distraction effects from irrelevant sounds have been found in children and to decrease with age from childhood to adulthood, whether investigated with audio–visual oddball paradigms (e.g., Olesen et al., 2006; Wetzel et al., 2006, 2019; Wetzel & Schröger, 2007, 2014) or with the Competitive Attention Task (Bidet-Caulet et al., 2015; Hoyer et al., 2021). For example, Hoyer et al. (2021) asked participants aged 6 to 25 years to accomplish the Competitive Attention Task. They found different developmental trajectories for the arousal and distraction effects. Phasic arousal was stable from 6 to 9 years of age, decreased between 9 and 13 years, and reached the adult developmental level at 13 years. Distraction progressively decreased from 7 to 12 years of age. This latter age-related change in distraction effects suggests that distractibility, or the propensity of isolated, unexpected, and task-irrelevant stimuli to disturb the voluntary attention mechanisms necessary to accomplish target tasks, decreases with increasing age during childhood. At a more general level, these findings are consistent with previous findings that attention development is characterized by a shift from a reactive strategy to a proactive strategy for attention control from childhood to adulthood (e.g., Blackwell & Munakata, 2014; Chevalier et al., 2013; Munakata et al., 2011). Such a shift relies on the development of both efficient sustained attention and inhibition abilities that enable children to shield against deleterious effects of distraction (Kanaka et al., 2008; Oakes & Tellinghuisen, 1994; Rueda et al., 2004; Slobodin et al., 2018; Thillay et al., 2015).

How irrelevant sounds facilitate and impair children's cognitive performance has never been investigated in arithmetic. This is surprising given that the ability to pay attention to relevant information and ignore irrelevant information is crucial for learning and academic achievement (Stevens & Bavelier, 2012) in general and arithmetic in particular. We pursued this goal in the current study. In two experiments, we investigated how irrelevant sounds influence children's arithmetic performance and how this influence changes with children's age. We asked third and fifth graders to verify arithmetic problems (e.g., 8 + 4 = 13. True? False?) and compared their performance under silence and sound conditions. We tested third and fifth graders because previous research in both attention (e.g., Hoyer et al., 2021; Lewis et al., 2017) and arithmetic (Gilmore et al., 2018) found that this is a crucial period that undergoes important changes. Children in this age range improve not only in resisting interference and focused attention but also in arithmetic fluency. Based on previous findings showing that irrelevant sounds induce phasic arousal and distraction effects in attention (e.g., Bidet-Caulet et al., 2015; ElShafei et al., 2020b), we manipulated distractor onset timing to investigate age differences in the effects of phasic arousal (Experiment 1) and distraction (Experiment 2).

Experiment 1: Effects of phasic arousal in arithmetic

The first goal of Experiment 1 was to test the hypothesis that sounds played at the beginning of problem display induced a burst of phasic arousal and led children to be faster in the sound condition relative to the silence condition. Whether this should interact with problem characteristics is impossible to predict, although it may be the case if harder false problems benefit more than easier true problems from this sound-related speed-up. This could happen if sounds lead children to increase speed at executing component processes (i.e., encoding, retrieval/calculation of correct sums, comparing calculated/retrieved and proposed sums, making true/false decisions, and response output) for verifying arithmetic problems, especially on false problems for which previous findings showed that component processes of making true/false decisions take more time (e.g., Zbrodoff & Logan, 1990).

In addition, Experiment 1 tested whether stability of effects of phasic arousal previously found in attention tasks from 6 to 9 years of age (e.g., Hoyer et al., 2021) generalizes to arithmetic problem-solving tasks. If that is the case, we expected comparable effects of phasic arousal in third and fifth graders in the current experiment.

Method

Participants

We tested 76 children (37 third graders and 39 fifth graders) from middle-class urban public schools in Marseille, France. Children's characteristics are summarized in Table 1.

The research in both experiments was approved by the National Ethics Committee.

Table 1
Participants' characteristics in Experiments 1 and 2.

	Experiment 1		Experiment 2	
	Third graders (n = 37)	Fifth graders (n = 39)	Third graders (n = 45)	Fifth graders (n = 47)
N (girls)	37 (11)	39 (16)	45 (20)	47 (19)
Age (*SD*) in years	7.9 (0.5)	9.9 (0.4)	7.9 (0.4)	10.0 (0.4)
Age range	7–9	9–11	7–9	9–11
Latencies in baseline arithmetic fluency (*SD*)	–	–	5668 (1917)	3704 (1277)

Stimuli

The basic set of problems included 12 individual addition problems presented in a standard form (i.e., $a + b$) with the operands a and b being one-digit numbers (e.g., 3 + 4; see Table A1 in the Appendix for the list of problems). Each individual problem was presented in $a + b$ and $b + a$ versions (e.g., 3 + 4 and 4 + 3). Each problem was presented with its correct sum (e.g., 3 + 8 = 11) and with an incorrect sum (e.g., 3 + 8 = 13). Proposed sums in false problems had a deviation of ± 1 or ± 2 units from correct sums. All true and false problems were presented once accompanied by a sound (e.g., playground noises) through headphones and once with no sound. All in all, each participant solved 96 problems: 12 (individual problems) × 2 (versions: $a + b$ and $b + a$) × 2 (true and false) × 2 (sound and silence). Given previous findings in simple arithmetic (for overviews, see Cohen Kadosh & Dowker, 2015; Gilmore et al., 2018), no tie problems (e.g., 3 + 3 = 6) were used and none of the operands was equal to 0, 1, 2, or 5.

Six sounds were selected from online soundbanks: https://www.soundjay.com, https://www.sound-effectsplus.com, https://tspace.library.utoronto.ca, and https://lasonotheque.org. Selected sounds were sounds of children or people chatting or playing (e.g., park, playground, and classroom sounds).

Procedure

Both experiments were run on a Windows 10 Microsoft Surface Go2 Touch-Screen (10.5 inches), Intel Core, m3-8100Y. Children were told that they would complete an arithmetic problem verification task. They were also told that they would hear sounds while solving some of the problems and no sounds while solving the other problems. Each trial started with a fixation cross at the center of the screen for 3000 ms. Then, the addition problem together with a proposed result were displayed in 40-point bold Arial font (black color) in the center of the screen, accompanied or not by a sound, until participants' response. Children needed to indicate whether the proposed result was correct or not as quickly and accurately as possible. To do this, they needed to press a delimited area (a 4-cm thick green stripe) on the right side of the touch-screen if the proposed result was correct and a delimited area (a 4-cm thick red stripe) on the left side of the touch-screen if the proposed result was incorrect.

The sounds started when the problems appeared on the screen and continued until participants responded. Children practiced the problem verification task on 10 trials (5 with sounds and 5 with no sounds). Children then solved the 96 randomly presented problems (in two blocks of 48 problems each with a short break in between).

Results

Mean response times for correct responses and percentages of errors (see Table 2) were analyzed via mixed-design analyses of variance (ANOVAs) involving 2 (Grade: third or fifth) × 2 (Problem Type:

[1] In both Experiments 1 and 2, we also analyzed z scores to control for potentially artifactual interactions (see Faust et al., 1999) due to differences in speed of processing between third and fifth graders. Analyses of means and z scores showed similar patterns for effects of irrelevant sounds on performance and for the Age × Irrelevant Sounds interaction. Therefore, only analyses of means are reported here. In addition, the same age-related differences in effects of irrelevant sounds came out significant when they were analyzed on proportional increased latencies in the sound condition relative to the silence condition (i.e., for each participant and each type of problem, the dependent variable was [(mean response times in the sound condition − mean response times in the silence condition) / mean response times in the silence condition].

Table 2
Mean solution times and percentages of errors for true and false problems under sound and silence conditions as a function of grades in Experiment 1.

Grade × Problem Type	Latencies (ms)			% Errors		
	Sound	Silence	Difference	Sound	Silence	Difference
Third graders						
True problems	6939	7075	−136	8.3	9.6	−1.3
False problems	6843	7280	−437	6.3	7.2	−0.9
Mean	6891	7178	−287	7.3	8.4	−1.1
Fifth graders						
True problems	4331	4252	79	6.6	7.7	−1.1
False problems	4577	4636	−59	4.8	5.8	−1.0
Mean	4454	4444	10	5.7	6.8	−1.1

false or true) × 2 (Irrelevant Sound: absent or present) with age as the only between-participants factor.[1] For each individual, latencies longer or shorter than the means of the condition ± 2.5 standard deviations were removed (mean = 1.42%).

Fifth graders were faster than third graders (4449 vs 7034 ms), $F(1, 74) = 40.824$, $p < .001$, $\eta_p^2 = .0356$. Participants were slower on false problems than on true problems (5802 vs 5614 ms), $F(1, 74) = 7.538$, $p = .008$, $\eta_p^2 = .092$, and under the silence condition than under the sound condition (5775 vs 5640 ms), $F(1, 74) = 4.776$, $p = .032$, $\eta_p^2 = .061$. The Grade × Irrelevant Sound interaction, $F(1, 74) = 5.497$, $p = .022$, $\eta_p^2 = .069$, showed that increased speed under the sound condition was found in third graders (−287 ms), $F(1, 36) = 7.765$, $p = .008$, $\eta_p^2 = .062$, but not in fifth graders (10 ms, $F < 1.0$).

Error rates were low (7.0%), and the only effects that came out significant were those of problem type and irrelevant sound. Children made more errors on false problems than on true problems (8.0% vs 6.0%), $F(1, 74) = 4.465$, $p = .038$, $\eta_p^2 = .057$, and under the silence condition than under the sound condition (7.6% vs 6.5%), $F(1, 74) = 4.854$, $p = .031$, $\eta_p^2 = .062$.

In sum, Experiment 1 revealed effects of phasic arousal in arithmetic similar to those found in attention tasks, and these effects occurred in younger third-grade children but not in older fifth graders.

Experiment 2: Distraction effects in arithmetic

In Experiment 2, we tested the hypothesis that unexpected irrelevant sounds played slightly after problem display would induce distraction effects. If children are distracted by such irrelevant sounds, their arithmetic performance should be poorer under a sound condition than under a silence condition. Such distraction effects have been found in the attention literature (e.g., Bidet-Caulet et al., 2015) to occur after initial burst of phasic alert. Distraction effects would occur via sounds capturing children's attentional resources that are temporarily not allocated to arithmetic problem solving. Deleterious effects of sounds were expected to interact with problem features such that they would be larger on false problems than on true problems. This is expected because false problems require more cognitive resources to make true/false decisions than true problems, and such additional processes require attentional resources temporarily captured by irrelevant sounds. Children should lack more cognitive resources to solve false, more resource-consuming problems than to solve true problems in the sound condition.

[1] In both Experiments 1 and 2, we also analyzed *z* scores to control for potentially artifactual interactions (see Faust et al., 1999) due to differences in speed of processing between third and fifth graders. Analyses of means and *z* scores showed similar patterns for effects of irrelevant sounds on performance and for the Age × Irrelevant Sounds interaction. Therefore, only analyses of means are reported here. In addition, the same age-related differences in effects of irrelevant sounds came out significant when they were analyzed on proportional increased latencies in the sound condition relative to the silence condition (i.e., for each participant and each type of problem, the dependent variable was [(mean response times in the sound condition − mean response times in the silence condition) / mean response times in the silence condition].

Experiment 2 also tested age-related differences in the effects of distraction on children's arithmetic performance. Following previous works on attention in children (e.g., Hoyer et al., 2021) showing age-related differences in distraction effects during attention tasks (i.e., they decreased after 8 years of age), such age-related differences were expected in the current context of arithmetic problem solving. More specifically, smaller effects of distraction were expected in fifth graders than in third graders. Such an age-related decrease in effects of distraction could occur given that both children's arithmetic proficiency (Gilmore et al., 2018) and attentional resources (Lewis et al., 2017) increase with increasing age during childhood.

In Experiment 2, we pursued the additional goal of determining how children control effects of distraction during mental arithmetic and how such control changes with children's age. We examined how distraction effects on current trials differ as a function of whether the immediately preceding trials were sound or silence trials. If children sequentially modulate attentional control during arithmetic problem solving to resist interference from irrelevant sounds, distraction effects should be smaller on current trials following sound trials relative to following silence trials. This could occur via top-down mechanisms if, for example, children prepare themselves to ignore the irrelevant sounds and maintain focused attention on arithmetic problem solving on current sound trials following previous sound trials. In other words, this hypothesis predicted a Previous Trial (sound or silence) $\times$ Current Trial (sound or silence) interaction, with smaller sound–silence differences on current trials after sound trials than after silence trials. Such sequential modulations have been previously found in a number of studies that used either domain-general tasks like the Stroop, Simon tasks, and episodic memory tasks (e.g., Brown et al., 2007; Gratton et al., 1992; Hinault et al., 2017; Stürmer et al., 2002) or domain-specific tasks like arithmetic problem solving (e.g., Hinault et al., 2016; Lemaire & Hinault, 2014). Finally, previous studies showed that such sequential modulation effects changed with children's age in both domain-general conflict monitoring tasks (e.g., Ambrosi et al., 2016, 2019, 2020) and domain-specific arithmetic tasks (e.g., Lemaire, 2016). Such age-related changes in sequential modulations are a consequence of responsible mechanisms (e.g., preparatory attention, executive control) becoming more efficient as children grow older (Federico et al., 2017; Moriguchi et al., 2016). In the current experiment, we expected that sequential modulations of distraction effects would change with children's age. More specifically, we predicted an Age $\times$ Previous Trial $\times$ Current Trial interaction, such that sequential modulations of effects of distraction on current trials would be larger in fifth graders than in third graders.

Method

Participants

We tested 92 children (45 third graders and 47 fifth graders) from middle-class urban public schools in Marseille (see children's characteristics in Table 1).

Stimuli and material

The same set of material (problems, sounds, headphones, and Microsoft Surface Go2 Touch-Screen) as in Experiment 1 was used with one exception. To test how effects of irrelevant sounds on current problems varied as a function of whether the immediately preceding previous problems were presented with sounds or with no sounds, we had four types of trials: sound–sound (i.e., both the current and previous problems were presented with sounds), sound–silence (i.e., the current problems were presented with no sounds and the previous problems were presented with sounds), silence–sound (i.e., the current problems were presented with sounds and the previous problems were presented with no sounds), and silence–silence (i.e., both the current and previous problems were presented with no sounds). The numbers of these types of trials were equal; each of these four types of trials included an equal number of true and false problems, and the order of trials was random.

Procedure

The same procedure as in Experiment 1 was used with two exceptions. First, the sounds started slightly after the problems appeared on the screen. Second, after solving the same 12 practice problems as in Experiment 1 under a silence condition, children verified 24 similar problems (12 true and 12 false; see list in Appendix A2), again under the silence condition. Finally, children solved an additional 8 practice problems (4 presented with no sounds and 4 presented with sounds; half true and half false). We asked children to solve 24 problems with no sounds to assess baseline latencies for verifying simple arithmetic problems. For each individual, the mean solution time for verifying the 24 baseline arithmetic problems was calculated. Then, 30% of this mean verification time was used as the duration between problem display and sound presentation. For example, if a child needed 3600 ms on average to solve the 24 baseline problems correctly, then the sound started 1080 ms after the problem appeared on the screen for the sound trials.

Results

Results are presented in two sections. First, we examine age-related changes in effects of distraction on arithmetic performance. Then, we examine age-related differences in sequential modulations of distraction effects.

Age-related changes in distraction effects

Distraction effects. Mean response times for correct responses and percentages of errors (see Table 3) were analyzed via mixed-design ANOVAs involving 2 (Grade: third or fifth) × 2 (Problem Type: false or true) × 2 (Irrelevant Sound: absent or present) with age as the only between-participants factor. For each individual, latencies longer or shorter than the means of the condition ± 2.5 standard deviations were removed (mean = 1.8%). Fifth graders were faster than third graders (4313 vs 6423 ms), $F(1, 90) = 36.902$, $p < .001$, $\eta_p^2 = .291$, and children were slower while solving false problems than while solving true problems (5508 vs 5182 ms), $F(1, 90) = 24.651$, $p < .001$, $\eta_p^2 = .215$, and slower under the sound condition than under the silence condition (5544 vs 5146 ms), $F(1, 90) = 9.216$, $p = .003$, $\eta_p^2 = .093$. The Grade × Problem Type interaction, $F(1, 90) = 3.970$, $p = .049$, $\eta_p^2 = .042$, and the Grade × Irrelevant Sound interaction, $F(1, 90) = 3.787$, $p = .055$, $\eta_p^2 = .040$, were significant. These interactions showed that the true/false differences were larger in third graders (461 ms), $F(1, 44) = 14.700$, $p < .001$, $\eta_p^2 = .250$, than in fifth graders (197 ms), $F(1, 46) = 4.105$, $p = .049$, $\eta_p^2 = .082$. In addition, the distraction effects (sound–silence) were larger in third graders (662 ms), $F(1, 44) = 6.423$, $p = .015$, $\eta_p^2 = .127$, than in fifth graders (145 ms), $F(1, 46) = 4.105$, $p = .049$, $\eta_p^2 = .082$.

Error rates were low (7.2%); they were larger in third graders than in fifth graders (8.8% vs 4.9%), $F(1, 90) = 9.023$, $p = .003$, $\eta_p^2 = .091$, and on true problems than on false problems (8.1% vs 5.6%), $F(1, 90) = 12.473$, $p < .001$, $\eta_p^2 = .122$. Moreover, three interactions came out significant: Grade × Problem Type, $F(1, 90) = 5.104$, $p = .026$, $\eta_p^2 = .054$, Problem Type × Irrelevant Sound, $F(1, 90) = 4.125$, $p = .045$, $\eta_p^2 = .044$, and Grade × Problem Type × Irrelevant Sound, $F(1, 90) = 5.477$, $p = .021$, $\eta_p^2 = .057$. This latter interaction was further analyzed with breakdown analyses in each grade separately with 2 (Problem Type) × 2 (Irrelevant Sound) within-participants ANOVAs. The effects of problem type, $F(1, 44) = 10.206$, $p = .003$, $\eta_p^2 = .188$, and the Problem Type × Irrelevant Sound interaction, $F(1, 44) = 10.206$, $p = .003$, $\eta_p^2 = .188$, came out significant in third graders. Third graders made more errors on true problems than on false problems (10.9% vs 6.7%). In addition, third graders made more

Table 3
Mean solution times and percentages of errors for true and false problems under sound and silence conditions as a function of grades in Experiment 2.

Grade × Problem Type	Latencies (ms)			% Errors		
	Sound	Silence	Difference	Sound	Silence	Difference
Third graders						
True problems	6483	5902	581	10.6	11.2	−0.5
False problems	7025	6282	743	8.5	4.9	3.6
Mean	6754	6092	662	9.6	8.1	1.5
Fifth graders						
True problems	4276	4152	124	5.3	5.4	0.0
False problems	4494	4328	166	4.3	4.6	−0.3
Mean	4385	4240	145	4.8	5.0	−0.2

errors in the sound condition than in the silence condition while solving false problems (8.5% vs 4.9%), $t(44) = 2.709$, $p = .010$, but erred equally ofen under the sound and the silence conditions for true problems (10.6% vs 11.2%, $t < 1.0$). In fifth graders, no effects came out significant on error rates ($ts < 1.0$).

Distributional analyses of distraction effects. We used the so-called Vincentization technique (Ratcliff, 1979) to characterize the dynamics of the distraction effects and to compare these dynamics in third and fifth graders. We analyzed distributions of the distraction effects (i.e., latencies for sound trials – latencies for silence trials) as a function of the overall distribution of latencies (delta plots; e.g., Gomez & Perea, 2020). The latencies for correct responses were sorted in ascending order and binned in four classes of equal size ($n = 24$ observations maximum). The mean of each bin (henceforth referred to as quartiles) was computed separately for each participant and each distraction condition. Average distributions of latencies were obtained by computing the mean values of quartiles by distraction condition (silence or sound) and age group separately. Preliminary analyses revealed similar distributions of distraction effects for true and false problems. Therefore, we report analyses collapsed over problem type.

Distraction effects were analyzed with ANOVAs with 2 (Grade: third or fifth) × 4 (Quartile: first, second, third, or fourth). The main effect of quartile, $F(3, 270) = 3.635$, $p = .013$, $\eta^2_p = .039$, and the Age × Quartile interaction, $F(3, 270) = 3.673$, $p = .013$, $\eta^2_p = .039$, were significant. This interaction was the result of a significant effect of quartile in third graders, $F(3, 132) = 3.970$, $p = .010$, $\eta^2_p = .083$, and nonsignificant effects of quartile in fifth graders ($F < 1.0$). As can be seen in Fig. 1, third graders showed that the longer the latencies, the larger the distraction effects (linear trend), $F(1, 132) = 48.785$, $p = .004$, $\eta^2_p = .062$.

Age-related differences in sequential modulations of distraction effects

The goal of this series of analyses was to determine whether the distraction effects on current trials are modulated by the type of immediately preceding trials (sound vs silence) and to compare such modulations in third and fifth graders. Mean latencies and percentages of errors on current trials (Table 4) were analyzed using 2 (Grade: third or fifth) × 2 (Previous Trials: sound or silence) × 2 (Current Trials: sound or silence) ANOVAs with grade as the only between-participants factor.

Analyses of latencies showed significant effects of grade, $F(1, 90) = 37.312$, $p < .001$, $\eta^2_p = .255$, current trials, $F(1, 90) = 9.727$, $p = .002$, $\eta^2_p = .013$, Grade × Previous Trials interaction, $F(1, 90) = 4.653$, $p = .034$, $\eta^2_p = .002$, and Grade × Current Trials interaction, $F(1, 90) = 4.353$, $p = .040$, $\eta^2_p = .006$. Most important, the Previous Trials × Current Trials interaction, $F(1, 90) = 10.109$, $p = .002$, $\eta^2_p = .002$, was significant.

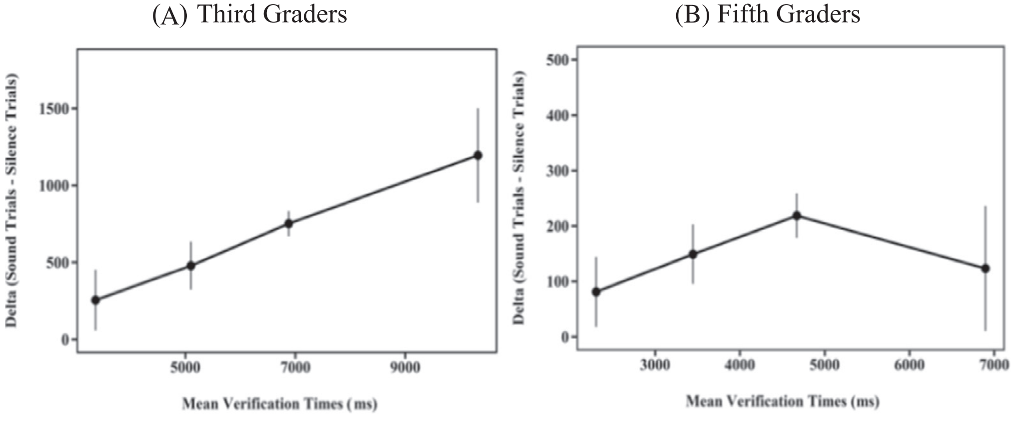

Fig. 1. Distributions of distraction effects (delta plots) in third graders (A) and fifth graders (B). This plot shows how the size of distraction effects (differences in latencies between sound and silence conditions) varies as a function of the overall distribution of latencies for the first, second, third, and fourth quartiles.

Table 4
Third and fifth graders' mean solution times (ms) and percentages of errors for current sound or silence trials following sound or silence trials in Experiment 2.

Grade × Previous Trials	Latencies (ms)			% Errors		
	Current trials					
	Sound	Silence	Difference	Sound	Silence	Difference
Third graders						
Sound	6785	6277	509	8.7	9.0	−0.3
Silence	6817	5941	877	10.3	7.2	3.1
Mean	6801	6109	693	9.5	8.1	1.4
Fifth graders						
Sound	4232	4237	−5	5.6	5.2	0.4
Silence	4544	4263	280	4.1	4.7	−0.6
Mean	4368	4250	137	4.9	5.0	−0.1

Note. Difference = Sound − Silence.

Although the Grade × Previous Trials × Current Trials interaction (F < 1.0) was not significant, we examined sequential modulations of distraction effects in each grade separately with 2 (Previous Trials) × 2 (Current Trials) within-participants ANOVAs. In third graders, the main effect of sound, $F(1, 44) = 6.962$, p =.011, η_p^2 =.024, was significant, and the Previous Trials × Current Trials interaction, $F(1, 44) = 3.751$, p =.059, η_p^2 =.002, was marginally significant. Contrast analyses revealed that distraction effects were larger on current trials after silence trials (877 ms), $t(44) = 3.003$, p =.004, than after sound trials (509 ms), $t(44) = 1.914$, p =.062. In fifth graders, the main effects of previous trials, $F(1, 46) = 6.783$, p =.012, η_p^2 =.004, and current trials, $F(1, 46) = 4.043$, p =.050, η_p^2 =.002, as well as the Previous Trials × Current Trials interaction, $F(1, 46) = 11.056$, p <.002, η_p^2 =.003, were significant. Distraction effects on current trials came out significant only after silence trials (280 ms), $t(44) = 3.549$, p =.001, but not after sound trials (−5 ms, t <1.0). Analyses of errors revealed only a significant main effect of grade, with third graders making more errors than fifth graders (8.8 % vs 4.9%).

In sum, Experiment 2 revealed (a) effects of distraction in children's arithmetic similar to those in attention tasks (irrelevant sounds presented slightly after problem display impaired children's performance), (b) smaller distraction effects in older children than in younger children, (c) increased effects of distraction with increasing latencies in younger children, and (d) smaller distraction effects on current trials after sound trials than after silence trials.

General discussion

To understand how distraction influences children's arithmetic performance, we examined how irrelevant sounds facilitate and impair children's cognitive performance while the children solve arithmetic problems. Third and fifth graders were asked to verify true/false one-digit addition problems (e.g., 9 + 4 = 12. True? False?) under silence and sound conditions. The sounds began when the problems started to appear on the screen (in Experiment 1) or slightly after (in Experiment 2) and continued until participants responded. The main findings showed phasic arousal and distraction effects that interacted with participants' age. More specifically, (a) children solved arithmetic problems more quickly in the sound condition than in the silence condition when the sound started with problem display (phasic arousal effects); (b) children were slower in arithmetic problem verification tasks when the sounds started slightly after the problems started to appear on the screen (distraction effects); (c) phasic arousal effects were found only in third graders, whereas distraction effects were found in both grades, although they were smaller in fifth graders; (d) distraction effects increased with increasing latencies in third graders but did not change in magnitude across the entire latency distribution in fifth graders; and (e) distraction effects on current trials were smaller after sound trials than after silence trials in both age groups (sequential modulations of distraction effects). These findings have important implications for furthering our understanding of effects of irrelevant sounds on arithmetic performance as well as cognitive processes involved in children's arithmetic.

The effects of irrelevant sounds on children's arithmetic performance

We found both phasic arousal and distraction effects. First, irrelevant sounds increased third graders' (but not fifth graders') speed while verifying arithmetic problems when sounds started with problem display (Experiment 1). This increased speed in arithmetic problem solving is similar to increased speed in sound detection tasks found in the attention literature (e.g., Bidet-Caulet et al., 2015; Max et al., 2015; Wetzel et al., 2012). In the attention literature, increased speed resulting from irrelevant sounds have been interpreted as a burst in phasic arousal. The faster latencies found here in the sound conditions of Experiment 1 could be similarly explained as a result of burst in phasic arousal. That is, sounds led children to respond more quickly via a transient nonspecific state of readiness to accomplish the arithmetic problem verification task.

The effects of phasic arousal on arithmetic performance were found here only in younger children (third graders) but not in older children (fifth graders). This was surprising because previous studies on attention development found quite large effects of phasic arousal on children aged 6 to 13 years (Bidet-Caulet et al., 2015; Hoyer et al., 2021; Masson & Bidet-Caulet, 2019). Note that Hoyer et al. (2021) found that effects of phasic arousal in sound detection tasks were stable from 6 to 9 years of age and decreased between 9 and 13 years. Lack of effects of phasic arousal in fifth graders in our arithmetic problem verification task suggests that fifth graders were in a similar state of readiness to accomplish the arithmetic problem-solving task in the sound and silence conditions. It is possible that this was the result of fifth graders' level of arithmetic fluency being high enough to leave no room for speed-up by irrelevant sounds.

The second important finding here was that unexpected irrelevant sounds led children to be slower in arithmetic problem verification tasks when the sounds were played slightly after the problems started to appear on the screen (Experiment 2). Such slowdown has also been found in the attention literature (e.g., Bidet-Caulet et al., 2015; ElShafei et al., 2020b; Escera et al., 2000; Masson & Bidet-Caulet, 2019) and have been interpreted as distraction effects. Similarly, here unexpected irrelevant sounds captured children's attention and triggered distraction during arithmetic problem solving. Distraction led to poorer performance via temporary reactive allocation of attention and resources to the irrelevant sounds before a reallocation of attention and resources toward the arithmetic problem verification task.

Although significant in both third- and fifth-grade children, effects of distraction were smaller in fifth graders. This is consistent with previously reported age-related decreases in distraction during attention (e.g., sound detection) tasks and extends it to the case of arithmetic problem solving. Such an age-related decrease in distraction effects during arithmetic problem solving could be the result of (a) increased arithmetic fluency in older children and (b) more efficient executive control mechanisms that enable older children to be more able to remain focused on target tasks and to be less distracted by irrelevant events. Gains in attentional resources in this age range have been reported many times in the general literature on attention development during childhood. Indeed, attentional processing is known to undergo dramatic changes from early childhood to early adulthood (e.g., Federico et al., 2017; Moriguchi et al., 2016). Previous findings found age-related increases in attentional resources necessary to maintain information and task goals active in working memory (e.g., Diamond, 2020), to inhibit processing irrelevant information or control interference from irrelevant information (e.g., Ambrosi et al., 2020; Richardson et al., 2018), to switch between cognitive entities (e.g., Doebel & Zelazo, 2015; Huizinga et al., 2006), or to remain focused on a target cognitive task (e.g., Lewis et al., 2017; van Belle et al., 2015). Increased efficiency in all these attentional mechanisms may have contributed here to help older children better resist interference from irrelevant sounds while verifying arithmetic problems.

Another interesting age difference was found here in distributions of distraction effects. The longer third graders took to verify arithmetic problems, the more they were distracted by irrelevant sounds, whereas magnitudes of distraction effects were independent of problem-solving latencies in fifth graders. If we assume that children took more time to solve harder problems, this suggests that the harder it was for third-grade children to verify arithmetic problems, the more sensitive they were to distraction effects, whereas effects of distraction in fifth graders were not modulated by the time it takes to solve an arithmetic problem and, presumably, by problem difficulty. Such age-related differences in distribution of distraction effects may result from arithmetic skills being much less fluent and less automatic in third graders. Previous findings in arithmetic development have found that effects of problem difficulty decrease with children's age (e.g., Koshmider & Ashcraft, 1991). Of course, future empirical studies should directly test the interaction between distraction and problem difficulty by comparing distraction effects when children solve easier and harder problems.

The final important finding in the current study concerns sequential modulations of distraction effects (Experiment 2). Distraction effects on current problems were smaller after sound trials than after silence trials. Such sequential modulations of distraction effects can be viewed as resulting from executive control mechanisms involved in how children process interference resulting from irrelevant sounds. Such trial-to-trial modulations of distraction effects likely occurred via children preparing themselves to ignore the irrelevant sounds and maintain focused attention on arithmetic problem solving on current sound trials following previous sound trials. This enabled them to shield against deleterious effects of irrelevant sounds while solving arithmetic problems. Note that such sequential modulations have been found in numerous studies examining attention mechanisms in conflict monitoring tasks like Stroop and Simon tasks (e.g., Ambrosi et al., 2016, 2019,2020; Brown et al., 2007; Gratton et al., 1992; Stürmer et al., 2002), as well as in arithmetic problem-solving tasks (e.g., Hinault et al., 2016; Lemaire, 2016; Lemaire & Hinault, 2014), in both adults and children. In other words, in arithmetic like in other domains, exerting trial-to-trial control could help children to decrease deleterious effects of distraction triggered by irrelevant sounds via blocking off or attenuating processing of task-irrelevant sounds. Interestingly, those previous studies found increased sequential modulations of interference effects with children's age. In the current study, although the Age × Previous Trials × Current Trials interaction was not significant, detailed analyses in each grade revealed qualitative differences between third- and fifth-grade children. Third graders showed distraction effects when current trials followed both sound and silence trials and showed smaller distraction effects after sound trials, whereas fifth graders showed distraction effects only when current trials followed silence trials. Such patterns suggest sequential modulations of distraction effects in both age groups and qualitative differences between the two age groups. Fifth graders were preparing themselves efficiently enough after sound trials to completely shield against interference from irrelevant sounds on following trials, whereas young children were less efficient at such preparation.

Cognitive processes in children's arithmetic

The current findings further document the role of control mechanisms in arithmetic problem solving. Previous studies showed that executive resources (e.g., control processes, working memory) influence children's arithmetic performance and that this influence changes with children's age (Barrouillet & Lépine, 2005; Bull et al., 1999; Bull & Lee, 2014; Bull & Scerif, 2001; Hodzik & Lemaire, 2011; Imbo & Vandierendonck, 2007; Lee & Bull, 2016; Lemaire, 2016; Peng et al., 2016). The current findings complement previous findings in showing effects of phasic arousal and distraction. Executive control processes are crucial in arithmetic problem solving to do several things like temporarily storing partial results while solving multidigit arithmetic problems, inhibiting incorrect response candidates in simple arithmetic, and switching between strategies from one trial to the next. The current results suggest that executive processes may also be crucial for children to process interference from irrelevant sounds on current trials and to prepare themselves for trying to minimize distraction from task-irrelevant sounds on following trials. Interestingly, we found that effects of phasic arousal and distraction differed in third and fifth graders. Such age-related differences may be the result of increases with children's cognitive growth in both arithmetic fluency and efficiency of control processes (Lemaire, 1996).

One surprising result here was that effects of both phasic arousal and distraction were found similarly for true and false problems. Given how problem features importantly influence arithmetic performance and how effects of problem features interact with other crucial factors in arithmetic (participants and situation characteristics), we expected that effects of phasic arousal and distraction would be larger while solving harder false problems. False problems take more time to verify than true problems because true/false decision making and response are harder to execute on false problems (e.g., Zbrodoff & Logan, 1990). Comparable effects of phasic arousal and distraction on true and false problems suggest that these effects are not specific to these true/false decision-making and response component processes. Note that this does not mean that effects of phasic arousal and distraction do not interact with any problem characteristics. Future studies may test other problem features by contrasting types of problems that are solved with largely different levels of performance. Thus, interactions of irrelevant sounds and other problem features (e.g., problem size, odd/even status of operands; auditory/visual presentation of problems) or task environments (e.g., speed/accuracy pressure, response deadlines) may be tested in future research to delineate boundary conditions of occurrence of phasic arousal and distraction effects during arithmetic development.

One important limitation of the current study concerns how phasic arousal and distraction influenced children's arithmetic performance. Above and beyond general mechanisms of attentional arousal and capture, the current findings cannot tell us whether irrelevant sounds resulted in children's using different strategies or mechanisms to verify arithmetic problems under sound and silence conditions or in children's using the same strategies but executing them with different levels of speed and accuracy. Strategic aspects of performance are very important in children's arithmetic and arithmetic development. Strategic aspects are known to vary with a number of parameters such as task environments and participants' age (e.g., Siegler, 2007). It is possible that irrelevant sounds led children to use faster strategies and to use these faster strategies more often in third graders (but not in fifth graders) when children verified arithmetic problems more quickly on sound trials in Experiment 1 and/or to use slower strategies and to use these slower strategies more often when the irrelevant sounds created distracting effects in both third and fifth graders in Experiment 2. In addition, such sound-related strategy differences may vary with children's age. Future studies may gain further insights regarding how irrelevant sounds affect children's performance in arithmetic problem solving and how effects of irrelevant sounds on arithmetic performance change with children's age by assessing strategies on each problem and by comparing strategy use and strategy execution under sound and silence conditions.

From a more practical perspective, one limitation of the current work is that different sounds may exert different types and levels of distraction. For example, future studies may compare the effects of distraction resulting from sounds that are completely irrelevant to the target cognitive task (like here) and sounds that are related to target cognitive tasks (e.g., using math words instead of sounds while solving arithmetic problems) or to oneself (e.g., hearing one's name vs hearing someone else's name). Such comparisons might be important if we want to advise teachers and other practitioners regarding what could be done to help children to better resist deleterious effects of distracting events in the context of classrooms and other environments above and beyond simply telling children to focus and not pay attention to stimuli or tasks other than the target task.

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Appendix A

See Tables A1 and A2.

Table A1
Set of 12 individual problems.

Operand	True answer	False answer
4 + 3	7	5
6 + 3	9	7
6 + 4	10	11
7 + 4	11	13
7 + 6	13	11
8 + 3	11	13
8 + 6	14	13
8 + 7	15	17
9 + 3	12	11
9 + 6	15	13
9 + 7	16	17
9 + 8	17	19

Note. Each problem was seen by each individual once in an *a* + *b* version (e.g., 4 + 3) and once in a *b* + *a* version (e.g., 3 + 4) and in the sound and silence conditions (96 problems per participant).

Table A2
Set of 12 problems used for baseline measures of latencies.

True problems		False problems	
3 + 5 = 8	4 + 9 = 13	3 + 5 = 9	4 + 9 = 11
3 + 7 = 10	5 + 8 = 13	3 + 7 = 12	5 + 8 = 12
5 + 7 = 12	5 + 9 = 14	5 + 7 = 11	5 + 9 = 16

Note. Each problem was seen by each individual once in an *a* + *b* version (e.g., 4 + 9 = 13) and once in a *b* + *a* version (e.g., 9 + 4 = 13) in the silence condition.

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