Why are children so distractible? Development of attentional capacities and phasic arousal from childhood to adulthood.

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Abstract

Distractibility is the propensity to behaviorally react to irrelevant information in a world flooded with sensory stimulation. Children are more distractible the younger they are. The precise contribution of attentional and motor components to distractibility and their developmental trajectories have not been characterized yet. We used a new behavioral paradigm to identify the developmental dynamics of components contributing to distractibility in a large cohort of participants (N=352; age range: 6-25). We assessed the specific developmental trajectories of voluntary attention and distraction, as well as impulsivity and motor control. Our results reveal that each of these components present distinct maturational timelines. These findings show that in young children, increased distractibility is mostly the result of reduced sustained attention capacities and enhanced distraction, while in teenagers, it is the result of decreased motor control and increased impulsivity.

Introduction

Remember the time you were in school, listening to your teacher; a car honking in the street or a classmate laugh might have caught your attention. These distractors interrupted your listening and note-taking. This tendency to have one's attention captured is commonly referred to as distractibility. Healthy adults can easily focus on the task at hand again, unless the task-irrelevant distractor is significant or vitally important and requires changing behavior (e.g. a fire alarm). This capacity to be both task-efficient and aware of the surroundings without being constantly distracted requires a balance between voluntary and involuntary forms of attention. Voluntary attention enables performing an ongoing task efficiently over time by selecting relevant information and inhibiting irrelevant stimuli; while involuntary attention is captured by an unexpected salient stimulus[1,2], leading to a distraction state. Compared to adults, children are more distractible[3–6], which can result from an imbalance between voluntary and involuntary attention. In ecological environments that are rich in distracting information, increased distractibility can be caused by (i) a reduced capacity to voluntarily pay attention to relevant events, (ii) an enhanced reaction to unexpected irrelevant distractors, or (iii) both. A better understanding of the causes of increased distractibility is crucial to improve rehabilitation or training programs to boost attention.

Two main components of voluntary attention are usually investigated: attentional orienting and sustained attention[2,7–9]. Orienting of attention operates by enhancing the processing of relevant information and inhibiting irrelevant events[2,9,10]. Posner paradigms with endogenous informative or uninformative cues[11,12] have been used to measure the voluntary orienting of attention in anticipation of a target in children. Results are conflicting: some show that the capacity to voluntarily orient attention is mature before the age of six[12,13] while others show that the benefit in reaction times (RT) to targets following informative cues increases from 6 years old to adulthood[11–17]. These findings suggest that the voluntary orienting of attention may improve during childhood, but its precise developmental trajectory remains unclear. Sustained attention is the ability to maintain the attentional focus over time on a given task[18–21]. It relies on tonic arousal, also called vigilance[22,23]. In children, sustained attention was mostly measured using detection tasks of targets among non-target stimuli presented at a fast rate (e.g. Continous Performance Test)[24]. A reduction in RT variability, as well as in the number of false alarms and missed responses, have been observed from 5 years old to early adulthood[7,8,18,25]. These findings suggest a continuous maturation of sustained attention throughout childhood and adolescence with critical maturation steps at 6 and 13 years old. To our knowledge, no study has investigated the developmental trajectory of sustained attention in a more ecological context including distracting events.

Only a few studies attempted to characterize the impact of distracting events in children[5,26]. Distraction was mostly investigated using audio-visual oddball paradigms, involving the discrimination of targets preceded by task-irrelevant standard or novel sounds[5,27–30]. Lower hit rate and longer reaction times to targets preceded by novel sounds are considered a measure of distraction. These measures were found to improve from childhood to adulthood[29,31,32], suggesting a reduction in distraction with age. It was recently questioned, however, whether these oddball paradigms provide a reliable measure of distraction, as after novels sounds, a behavioral cost (an increase in RT) was not always observed[30,33–37], and even enhanced performances were found[30,37–39]. There is growing evidence that this facilitation effect may be due to a phasic increase of arousal triggered by unexpected salient events[30,37–40]. This burst of arousal may be mediated by the norepinephrine system and result in a transient and non-specific state of readiness to respond to any upcoming stimulus[41–43]. Thus, the so-called distracting sounds generate a combination of facilitation and distraction effects, which final impact on the performance of an unrelated task depends on the task demands[38,44–47], the sound properties[30,35,38], the sound-target delay[35,40,48] and is probably contingent to brain maturation processes. Previous works have shown that an increase in phasic arousal can also lead to increased false alarm rate[41,49]. Impulsivity is the tendency to act without forethought and to fail to appreciate circumstances related to the present situation[50–52]. An increased false alarm rate is typically observed in impulsive persons and could result from an enhanced phasic arousal[53–55] coupled – or not – with a lack in motor control[7,56–59]. The developmental trajectories of distraction, phasic arousal and impulsivity triggered by unexpected salient event have not been disentangled yet.

In sum, previous behavioral studies showed that voluntary orienting of attention, sustained attention, distraction, phasic arousal and impulsivity follow different developmental trajectories that remain to be specified. Despite the importance of distractibility, its developmental trajectory is currently unknown. The aim of the present study is to specify the maturational timeline of the different components of distractibility in people from 6 to 25 years old. We used an adaptation of a recently developed paradigm, the Competitive Attention Task (CAT)[48]. This paradigm combines the Posner task and the oddball paradigm to provide simultaneous and dissociated measures of voluntary attention, distraction, phasic arousal, impulsivity and motor control (Fig. 1). To assess voluntary attention orienting, the CAT includes informative and uninformative visual cues respectively indicating - or not - the spatial location of a forthcoming auditory target to detect. To measure distraction, the CAT comprises trials with a task-irrelevant distracting sound preceding the target according to several delays (Dis1, Dis2 & Dis3). This change in distractor timing onset allows to dissociate the effects of distraction and phasic arousal in comparison to the condition with no distractor (NoDis). Moreover, similarly to other detection tasks, the rates of different types of false alarms, late and missed responses provide measures of sustained attention, impulsivity and motor control. The CAT measures allow to characterize the developmental trajectories of voluntary attention and distraction, and to determine whether the increased distractibility observed during childhood results from either (i) reduced capacities in voluntary attention, (ii) increased reaction to distracting information, or (iii) both.

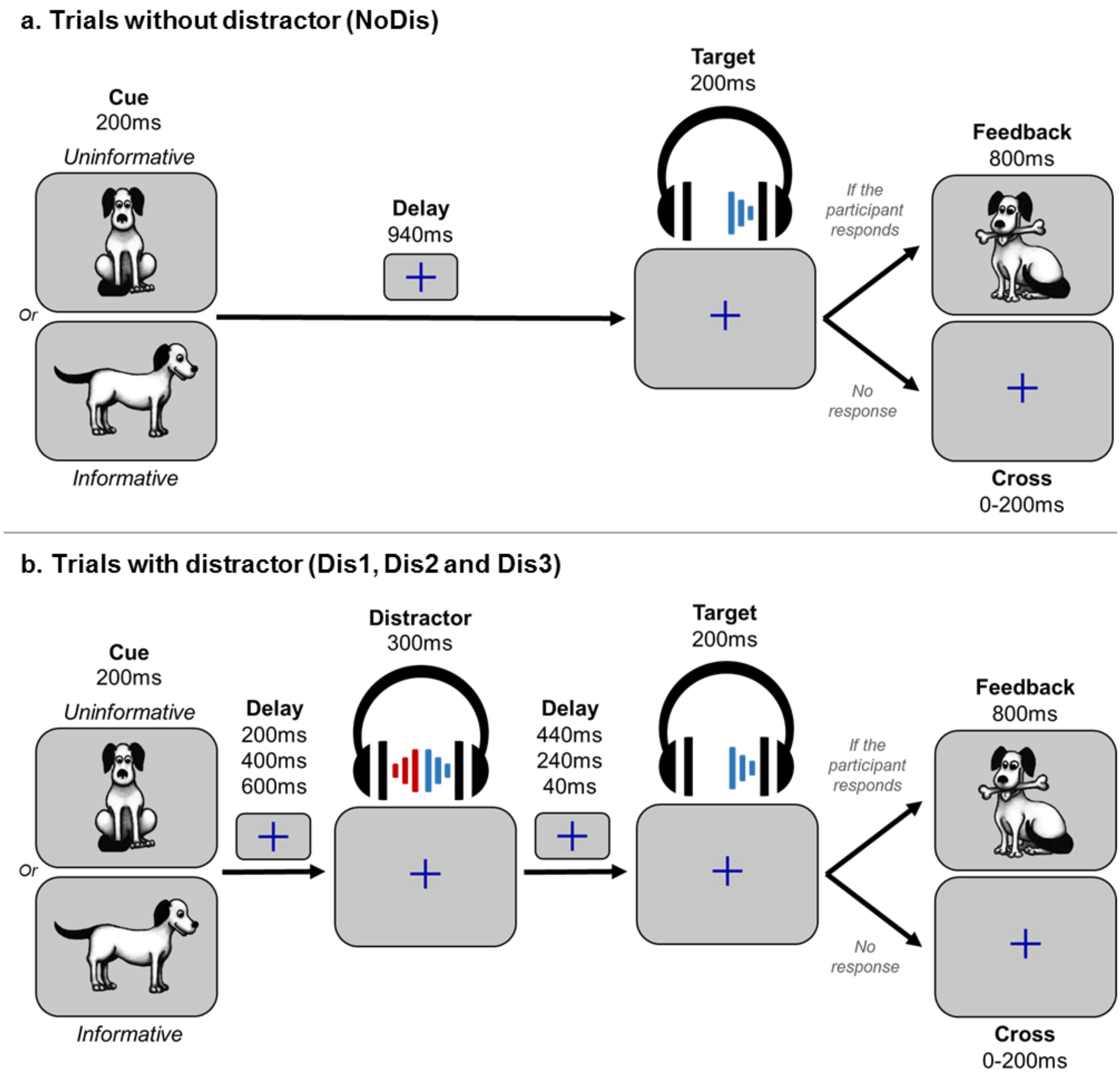

Fig. 1 | Protocol. a, In uninformative trials, a facing-front dog was used as visual cue (200 ms duration), indicating that the target sound will be played in either the left or right ear. In informative trials, a facing left or right dog visual cue (200 ms duration) indicated in which ear (left or right, respectively) the target sound will be played (200 ms duration) after a delay (940 ms). If the participant gave a correct answer, a feedback (800ms duration) was displayed. **b**, In trials with distractor the task was similar, but a binaural distracting sound (300 ms duration) - such as a phone ring - was played during the delay between cue and target. The distracting sound could equiprobably onset at three different times: 200 ms, 300 ms, or 600 ms after the cue offset.

Results

352 subjects were included in this study and divided into 14 age groups shown in Table 1. Using Bayesian contingency table tests, we found decisive evidence for a uniform distribution of the sample population across all age ranges in block order ($BF_{10} = 2.1 \cdot 10^{-5}$), gender ($BF_{10} = 5.2 \cdot 10^{-7}$) and handedness ($BF_{10} = 8.1 \cdot 10^{-21}$). We observed - in the 6 to 17 year olds – a decisive evidence for a uniform distribution across age ranges in socio-economic status ($BF_{10} = 8.9 \cdot 10^{-20}$) and education level of the parents ($BF_{10} = 1.5 \cdot 10^{-19}$).

Table 1 | Characteristics of the population sample. Detailed samples by age for gender, handedness, mean parent education level for children and mean education level for adults, total ADHD scale scores and thresholds of auditory perception (± standard error of the mean, SEM).

Age	Samples		Gender		Handedness		Mean education	ADHD score	Threshold of auditory perception (dBA)	
Range	*Included*	*Excluded*	*Male*	*Female*	*Right*	*Left*	*Max education level = 5*	*Max score Children = 54 Adults = 72*	*Right ear*	*Left ear*
6	24	5	54%	46%	88%	12%	3.3 ± 0.2	17.8 ± 1.7	26.8 ± 2.3	26.0 ± 3.0
7	22	12	55%	45%	91%	9%	3.5 ± 0.2	17.0 ± 2.0	26.9 ± 2.2	29.4 ± 2.4
8	24	6	54%	48%	88%	12%	2.7± 0.2	18.5 ± 1.2	24.8 ± 2.5	26.3 ± 2.5
9	28	5	54%	45%	75%	25%	3.6 ± 0.2	17.9 ± 1.6	25.2 ± 2.3	25.5 ± 2.5
10	36	1	47%	53%	92%	8%	3.0 ± 0.2	16.4 ± 1.4	25.1 ± 1.9	21.9 ± 1.5
11	25	2	40%	60%	92%	8%	3.4 ± 0.2	12.8 ± 1.8	29.1 ± 2.9	29.1 ± 2.3
12	28	3	54%	46%	89%	11%	3.3 ± 0.2	9.1 ± 1.7	33,1 ± 2.1	32.3 ± 1.9
13	25	3	52%	48%	92%	8%	2.9 ± 0.3	10.2 ± 1.8	32.2 ± 2.0	31.3 ± 1.8
14	25	7	44%	56%	92%	8%	3.8 ± 0.2	7.8 ± 1.2	29.4 ± 2.4	28.2 ± 2.1
15	24	4	58%	42%	92%	8%	3.0 ± 0.2	9.5 ± 1.5	28.2 ± 2.7	27.0 ± 2.4
16	22	2	50%	50%	95%	5%	3.7 ± 0.2	9.9 ± 1.4	31.4 ± 2.7	31.5 ± 2.9
17	26	7	38%	59%	88%	12%	2.7 ± 0.2	8.1 ± 1.7	32.9 ± 2.5	31.3 ± 2.2
18-19	23	2	39%	61%	83%	7%	1.4 ± 0.2	34.5 ± 3.4	22.5 ± 2.5	20.0 ± 1.6
20-25	20	1	50%	50%	80%	20%	4.0 ± 0.3	30.6 ± 3.0	19.7 ± 1.5	19.7 ± 1.4

We extracted 8 behavioral measures from participants' responses (see Extended Data Fig. 1): median reaction times (RT), RT standard deviation (RT SD) as a measure of sustained attention, late response % (LateRep) as a measure of attentional lapses, missed response % (MissRep) and distrastor response % (DisRep) as measures of distraction, cue response % (CueRep) and anticipated response % (AntRep) as measures of impulsivity, and random response % (RandRep) as a measure of motor control (see Extended Data Fig. 1).

For each type of behavioral measurement, we analyzed the influence of AGE, GENDER, CUE and DISTRACTOR factors (unless specified otherwise in the Table 2) using linear mixed error-component models or generalized linear mixed models.

In the following, the results of the Wald T-tests on the different models are presented. When a factor was involved in a main effect and a higher order interaction, we only specified the post-hoc analysis related to the interaction.

Table 2 | Main statistical analyses according to behavioral response types. Experimental conditions, factors and models used as a function of the behavioral measurement. *Response type cumulating less than 1 % of response proportion across the total sample (only 2-way interactions were considered). Detailed factor levels: CUE = informative vs. uninformative; CUELRN = left, right and neutral; Block = first, second and third. Models: LME = Linear Mixed Error-component model; GLMM = Generalized Linear Mixed Model.

Response type	Condition(s) used for response type calculation	Fixed factor(s)		Random factor	Analysis	Distribution fitting	Missing data
		Between subjects	*Within subjects*				
median RT (log)	NoDis vs. Dis1 vs. Dis2 vs. Dis3	Age, Gender	Cue, Distractor	Distractor + Subject	LME	Gaussian	2.3 %
RT SD	NoDis	Age, Gender	Block	Subject	LME	Gaussian	0.0 %
Late responses	NoDis	Age, Gender	Cue	Subject	GLMM	Binomial	0.0 %
Missed responses	NoDis vs. Dis1 vs. Dis2 vs. Dis3	Age, Gender	Cue, Distractor	Subject	GLMM	Binomial	0.0 %
Cue responses *	NoDis & Dis1 & Dis2 & Dis3	Age, Gender	CueLRN	Subject	GLMM	Binomial	0.0 %
Distractor responses	Dis1 & Dis2 & Dis3	Age, Gender	CueLRN	Subject	GLMM	Binomial	0.0 %
Anticipated responses	NoDis vs. Dis1	Age, Gender	CueLRN, Distractor	Distractor + Subject	GLMM	Binomial	0.0 %
Random responses *	NoDis & Dis1 & Dis2 & Dis3	Age, Gender	CueLRN	Subject	GLMM	Binomial	0.0 %

Median RT.

RT were modulated by GENDER ($\chi2$ (1) = 18.1; p < .001): male (325.6 ± 1.6 ms) were faster than female (350.8 ± 1.7 ms) participants.

We observed main effects of the AGE ($\chi 2$ (13) = 460.0; p < .001, Extended Data Fig. 2), the CUE ($\chi 2$ (1) = 56.1; p < .001) and the DISTRACTOR ($\chi 2$ (3) = 1326.5; p < .001) factors on RT. We did not observe a CUE by AGE interaction (Fig. 3a). This was confirmed by positive evidence against a correlation of the voluntary attention orienting index with age (Kendall's Tau = 0.041, BF_{10} = 0.1).

A DISTRACTOR by CUE interaction was significant ($\chi 2$ (3) = 26.6; p < .001; Fig.2). Post-hoc Honest Significant Difference (HSD) tests showed that participants were faster to detect targets preceded by an informative cue in the NoDis, Dis2 and Dis3 (p <.001) conditions, while no cue effect was found in the Dis1 condition (p = .694).

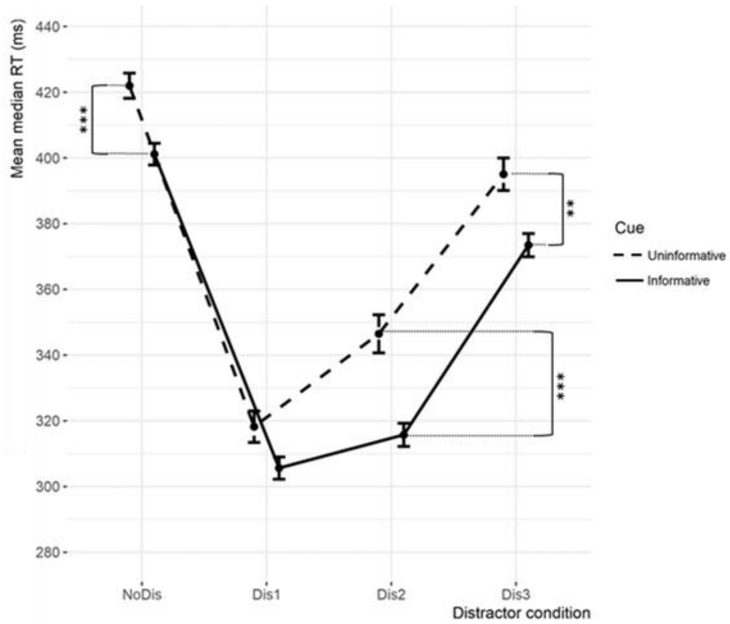

Fig. 2 | Median RT according to cue and distractor conditions. Mean of median reaction time as a function of the cue category [informative or uninformative] and of the distractor condition [NoDis, Dis1, Dis2, Dis3] (p < .05 *, p < .01 **, p < .001 ***; Error bars represent 1 SEM).

A DISTRACTOR by AGE interaction was significant ($\chi 2$ (39) = 81.8; p < .001). Two specific measures of the distractor effects were considered for post-hoc analysis: the distractor occurrence (median RT > 0 in NoDis minus median RT > 0 in Dis1) and the distractor position (median RT > 0 in Dis3 minus median RT > 0 in Dis1), to assess the effect of age on phasic arousal and distraction effects, respectively. First, the Shapiro-Wilk test was applied to check the normality of the distribution and indicated that the arousal and distraction measures were not normally distributed (W = 0.94; p < .001 and W = 0.98; p < .001, respectively). Then, planned non-parametric Kruskal-Wallis tests were performed on arousal and distraction effects.

AGE ($\chi 2$ (13) = 91.0; p < .001; Fig. 3c) had a significant effect on the arousal facilitation effect: it was larger in the 6, 7 and 8 year olds compared to the 13 to 25 year olds. Other significant effects are shown in Fig 3c. This result was confirmed by decisive evidence for a negative correlation of the Arousal effect index with age (Kendall's Tau = -0.141, BF_{10} = 132.7).

The distraction effect was also significantly modulated by the AGE factor ($\chi 2$ (13) = 47.4; p < .001; Fig. 3d): children of 6 years of age showed higher scores than the 12 to 25 year olds. This was not confirmed by Bayesian statistics: a positive evidence against a correlation of the Distraction effect index with age (Kendall's Tau = -0.044, BF_{10} = 0.1) was found.

RT SD in the NoDis condition.

A significant main effect of AGE was found on RT SD ($\chi 2$ (13) = 287.1; p < .001; Fig. 3b). HSD post-Hoc comparisons revealed that RT SD was larger in the 6 to 8 year olds compared to the 10 to 20-25 year olds; RT SD was also significantly higher in the 9 year olds compared to the 13 to 25 year olds. The RT SD decreases between 8 and 13 years old.

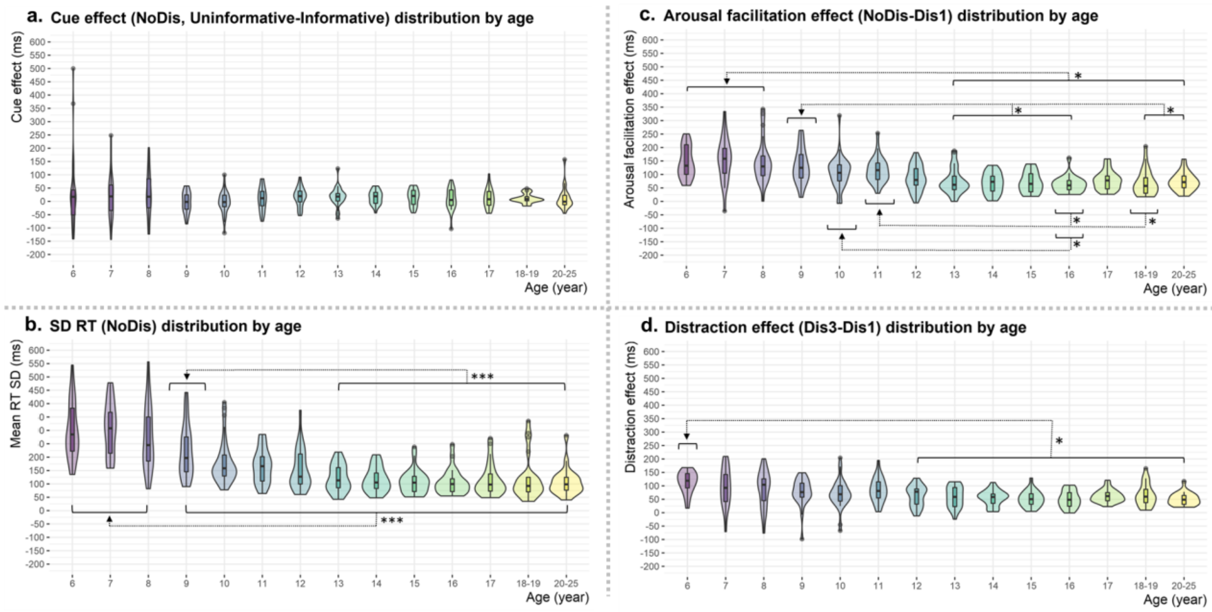

Fig. 3 | RT effects according to age. a, Reaction time differences between NoDis uninformative and informative (cue effect) as a function of the age range. **b**, Reaction time variability (RT standard deviation across blocks) as a function of age range. **c**, Reaction time differences between NoDis and Dis1 (arousal effect) as a function of the age range. **d**, Reaction time differences between Dis3 and Dis1 (distraction effect) as a function of the age range. (p < .05 *, p < .01 **, p < .001 ***). Within each boxplot (Tukey method), the horizontal line represents the median, the box delineates the area between the first and third quartiles (interquartile range); juxtapose to each boxplot, the violin plot adds rotated kernel density plot on left and right side.

Response types.

The distribution of the different types of responses changes with age, with an improvement in accuracy with age (Fig. 4). The average correct response rate was 76.0 ± 0.3 %. No main effect of AGE, nor interaction with AGE, was found for CueRep (total average: 0.7 ± 0.1 %) and LateRep (total average: 11.0 ± 0.2 %). Significant effects of age on the other response types are detailed in the following.

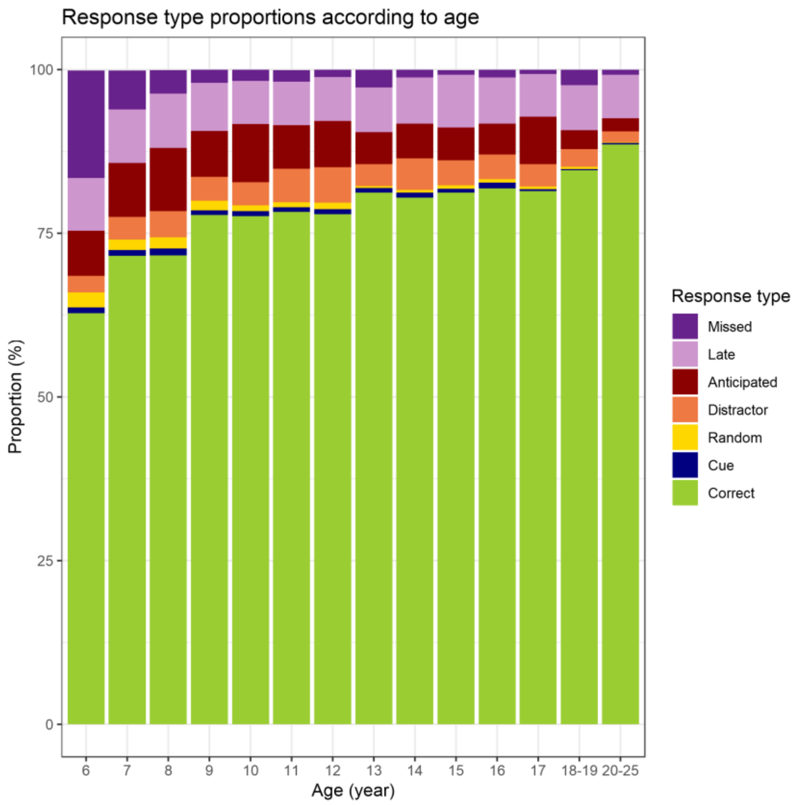

Fig. 4 | Response type proportions according to age.

Missed responses.

The rate of missed responses (3.5 ± 0,1 %) was modulated by AGE (χ2 (13) = 96.0; p < .001) and DISTRACTOR (χ2 (3) = 133.8; p < .001). An interaction between the DISTRACTOR and the AGE factors was significant on MissRep rate (χ2 (39) = 343.9; p < .001, Fig. 5a). HSD post-hoc tests indicated significant larger MissRep rate in the Dis conditions compared to the NoDis condition in the 6 and 7 year olds, only. In the NoDis condition, HSD post-hoc comparisons indicated no significant difference in the MissRep rate with age. In the distractor conditions, a higher percentage of MissRep was found in the 6 to 7 year old children. More precisely, the 6 year olds had a higher MissRep rate than the 8 to 20-25 year olds in all the distractor conditions, while the 7 year olds presented more MissRep than (i) the 10, 12, 15, 17 and 20-25 year olds in the Dis1 condition, (ii) the 10 and 17 to 20-25 year olds in the Dis2 condition, and finally (iii) the 10 and 15 to 25 year olds in the Dis3 condition. In summary, only the 6 and 7 year olds missed target sounds preceded by a distracting sounds.

Anticipated responses (NoDis & Dis1 conditions).

The rate of anticipated responses (10.3 ± 0,3 % on average) was modulated by the AGE (χ2 (13) = 52.9; p < .001; Fig 5b). Post-hoc HSD analysis showed that the 7 to 12 and the 17 year olds had more AntRep than the 20-25 year-olds. Children from 7, 8 and 10 years old showed an increased AntRep rate compared to the 18-19 year olds. Finally, the 10 year olds showed a higher AntRep rate than the 13 year old children.

We also observed a significant effect of GENDER on AntRep rate (χ2 (1) = 10.3; p = .001) indicating larger AntRep rate in male (11.7 ± 0.4 %) compared to female (8.9 ± 0.4 %) participants.

We observed significant main effects of the CUE (χ2 (1) = 18.7; p < .001) and the DISTRACTOR (χ2 (1) = 702.6; p < .001), as well as a significant DISTRACTOR by CUE interaction (χ2 (1) = 15.3; p < .001) on AntRep. Independently of the cue nature, participants made more Antrep in the Dis1 (left: 21.2 ± 0.9 % / right: 17.2 ± 0.8 % / neutral: 18.3 ± 0.8 %) than in the NoDis (left: 2.2 ± 0.2 % / right: 2.2 ± 0.2 / neutral: 1.4 ± 0.2; p < .001) condition. The AntRep rate was found larger with informative cues rather than with uninformative ones in the NoDis condition (both left and right informative cues: p < .001); while it was greater with left cues compared to right and neutral cues in the Dis1 condition (both: p < .001).

Distractor responses.

The rate of distractor responses (7.0 ± 0.2 % on average) was found modulated by the AGE (χ2 (13) = 30.8; p = .004; Fig. 5c): the 11 (9.7 ± 0.8 %; p <.01) and 12 (10.0 ± 0.8 %; p <.01) year old children made more DisRep than the 20-25 year olds (3.2 ± 0.5 %).

We also observed a significant main CUELRN (χ2 (13) = 48.5; p < .001) effect: all participants made more Disrep in the left cue condition (8.8 ± 0.3 %) than in the right (7.0 ± 0.3 %; p < .001) and the neutral (6.1 ± 0.3 %; p < .001) ones.

Random responses.

The rate of random responses (0.8 ± 0.1 % on average) was modulated by the AGE (χ2 (13) = (77.2); p < .001; Fig. 5d). The 6 year olds (2.0 ± 0.3 %) made more RandRep than the 13 (0.3 ± 0.1 %), 14 (0.5 ± 0.2 %), 15 (0.6 ± 0.2), 16 (0.5 ± 0.2), 17 (0.3 ± 0.1 %),18–19 (0.3 ± 0.1 %) and 20-25 (0.1 ± 0.1) year olds. The 7(1.8 ± 0.3), 8 (1.4 ± 0.2 %) and 9 (1.2 ± 0.2) year olds made more RandRep than both the 13 and 14 year olds, and the 17 to 25 year olds. Additionally, the 12 year olds (0.8 ± 0.1) made more RandRep than the 20-25 year olds.

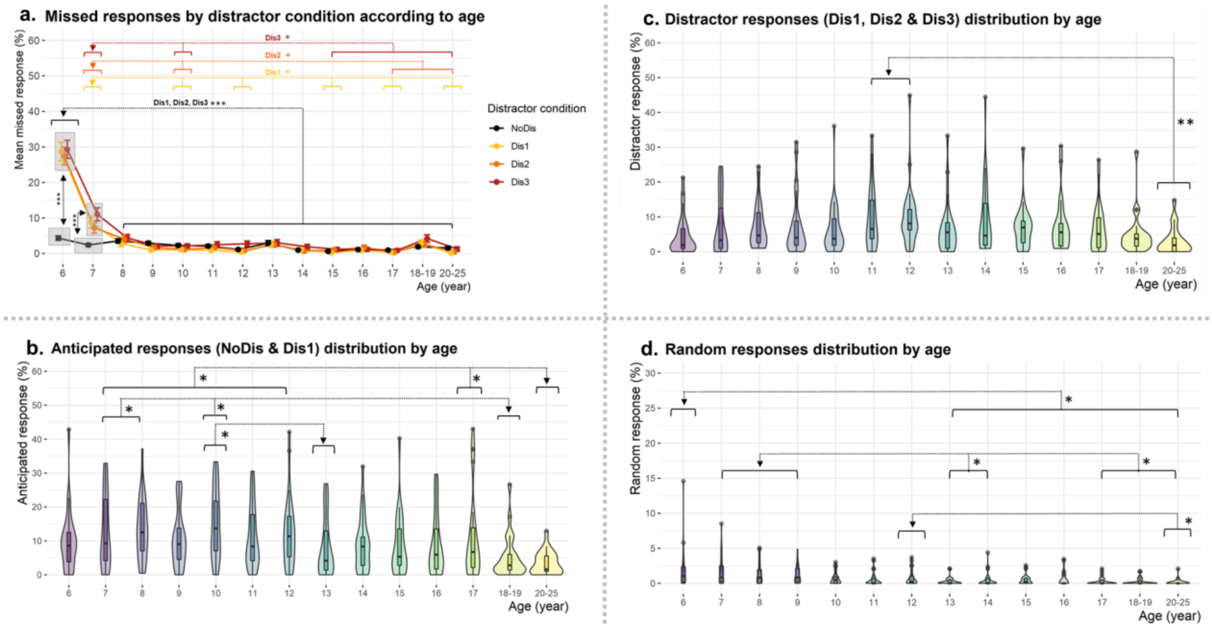

Fig. 5 | Behavioral responses according to age. **a**, Mean missed responses percentage as a function of the distractor condition and the age range (error bars represent 1 SEM). **b**, Anticipated responses percentage (NoDis and Dis1) as function of the age range. **c**, Distractor responses percentage as a function of the age range. **d**, Random responses percentage as a function of the age range. ($p < .05$ *, $p < .01$ **, $p < .001$ ***). For b, c and d: within each boxplot (Tukey method), the horizontal line represents the median, the box delineates the area between the first and third quartiles (interquartile range); juxtapose to each boxplot, the violin plot adds rotated kernel density plot on each side.

The percentage of correct responses increases with age. Incorrect responses are due to distracting sounds inducing a large number of missed responses in the youngest ones (age 6 and 7) and a great amount of responses to distractors in the 11 and 12 year olds. Moreover, the 6-9 year olds present a higher rate of random responses and the 7-12 year olds a greater rate of anticipated responses (see Fig. 6 for a graphical representation of the main results according to age).

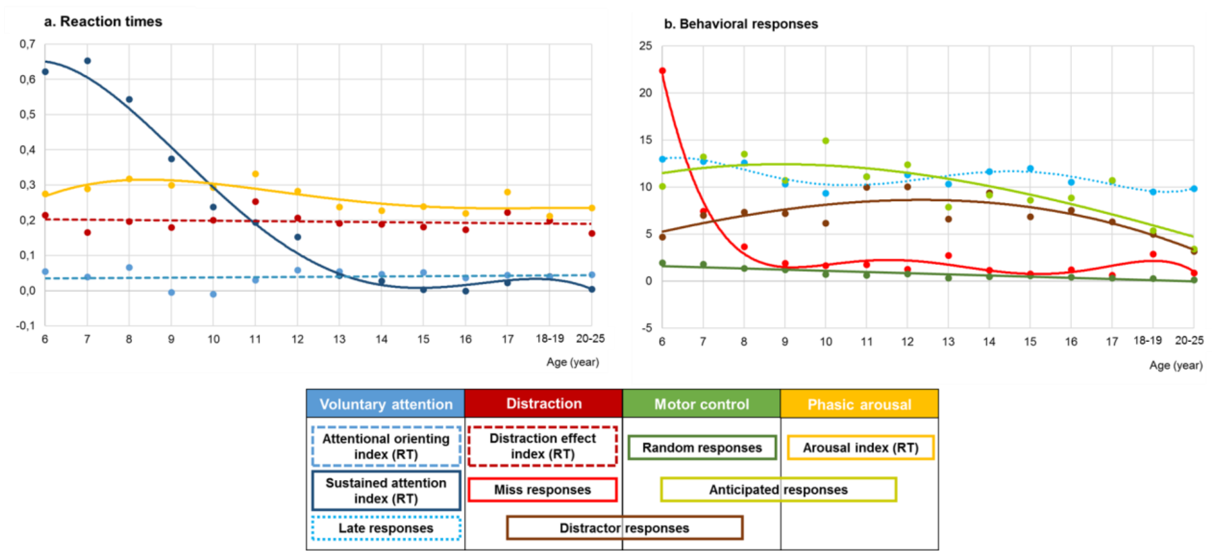

Fig. 6 | Graphical representation of the main results. **a**, Reaction times indexes according to age. Curves correspond to polynomial fitting curves for the Sustained Attention (order 4) and Arousal (order 4) indexes, and to fitting lines for the Distraction and Attention Orienting indexes. Sustained attention index = mean RT SD for each age range normalized across age ranges; Attention orienting Index = ($medianRT_{NoDisUninf} – medianRT_{NoDisInf}$) / $medianRT_{All}$; Arousal index = ($medianRT_{NoDis} – medianRT_{Dis1}$) / $medianRT_{All}$; Distraction effect index = ($medianRT_{Dis3} – medianRT_{Dis1}$) / $medianRT_{All}$. **b**, Percentage of late responses (LateRep), miss responses (MissRep), responses to distractors (DisRep), anticipated responses (AntRep) and random responses (RandRep) according to age. Dots represent the mean percentage. Curves correspond to polynomial fitting curves for LateRep (order 5), MissRep (order 5) DisRep (order 3) and AntRep (order 3), and to a fitting line for RanRep. Measures reflecting (1) voluntary attention are in blue colors, (2) distraction are in red colors; (3) motor control are in green colors, and (4) arousal are in yellow color. Brown and light green colors represent processes overlaps. Dotted lines represent measures which have not been found modulated by age.

Discussion

We aimed to characterize the developmental trajectories of attentional and motor processes related to distractibility using several behavioral measures (see a graphical summary in Fig. 6). Our findings suggest that voluntary orienting of attention is mature at 6 years old while voluntary sustained attention slowly develops until 13 years old. Distraction is increased before the age of 8, compared to older age groups. Later in childhood and adolescence, there is increased impulsivity, which fades in adulthood.

Shorter reaction times to targets preceded by informative rather than uninformative cues is typically used as a measure of voluntary attention orientation towards the cued side in the informative condition[2,9,60]. According to Bayesian correlation analysis performed in the current study, there is no evidence for an effect of age on this cue effect in the absence of distracting sounds, corroborating previous studies showing mature voluntary attention orienting at 6 years old, or even during the first year of life[11–17].

In the absence of distracting sounds, difficulties in sustained attention can result in increased RT variability and late response rate (index of attentional lapses). Increased intra-subject variability of RT reflects voluntary attentional efficiency[61–63]. We found that RT variability between trials with no distracting sounds during the whole experiment (around 15 min) slowly decreases between 8 to 13 years old corroborating an improvement in sustained attention during this period[8,25,64]. This progressive maturation of sustained attention between 8 and 13 years old may be related to the structural and functional maturation of the frontal lobes[65–67], allowing a more efficient voluntary attentional control[25,65,68]. Interestingly, we did not find an increase in RT variability through the task as previously observed in adults[69]. This absence of modulation over time could be explained by the presence of distracting sounds in 50% of the trials in the CAT, compared to typical paradigms used to measure sustained attention such as the Continuous Performance Test[7,8,70]. Distractors trigger a phasic arousal burst[48], which increases alertness for a few seconds[41]. This could help maintaining an appropriate general arousal level compensating the vigilance decline across the blocks. Even when selecting the trials without distractors to analyze sustained attention, phasic arousal could still have an effect especially when the trials without distractors were preceded by a late occurrence distractor trial[40]. We also found no evidence for an effect of age on the rate of late responses reflecting attentional lapses, contrasting with previous studies highlighting a global decrease in spontaneous fluctuation of attention between 8 to 13 years old[64]. Phasic arousal could also partially compensate for decreased sustained attention capacities by reducing RT variability enough to avoid attentional lapses. Therefore, the CAT seems to provide a specific assessment of the efficacy of sustained attention in a context with distractors.

Several measures of the CAT reflect distraction (i.e. a behavioral cost). Distracting sounds can result in longer reaction times[40,48,71,72], or worse, to missed responses to the following target[35,73] and sometimes to responses to the distractor[56]. The strength of the CAT lies in the different timings of the distractor sounds before the target, allowing to dissociate the behavioral cost and benefit they induce. In line with previous studies using the CAT in adults[40,48,72,74], we observed two distinct effects on RTs triggered by the distracting sounds. First, distracting sounds played long before the target (Dis1 and Dis2) induced a reduction of reaction times compared to a condition without distractor (NoDis): this benefit in RT has been attributed to an increase in phasic arousal[40]. Second, distracting sounds played just before the target (Dis3) resulted in an increase in reaction times compared to conditions with a distractor played earlier (Dis1 and Dis2): this cost in RT is considered a behavioral index of distraction[40,48,7240,48,71]. Both phasic arousal and distraction effects were observed between 6 and 25 years old. The CAT thus allows to dissociate the effect of arousal (RT NoDis – Dis1) and distraction (RT Dis3 – Dis1) on the RT in both adults and children. Importantly, the developmental trajectories of these two measures were found to be different. Distraction is increased in the 6 years old, only, and progressively decreases from age 7 to 12, although this effect is not seen when normalizing using the median RT across all trials. Phasic arousal is stable between ages 6 and 9, decreases between ages 9 and 13 and reaches the adult developmental level at 13 years old.

Some studies using an auditory oddball paradigm have reported decreasing distraction (difference in reaction time between distractor and standard trial) with increasing age[3,29,32]; while reduced distraction has also been observed in 9 to 10 year old children compared with adults[75]. Other studies have not reported age-associated differences in behavioral distraction[75–77]. The oddball paradigms used to investigate the behavioral impact of distractors across development, were however, not designed to dissociate the phasic arousal and distraction effects[30,40,48]. Depending on the distractor-target interval in the task design, response times display a continuum between gain and cost, induced by beneficial arousal and detrimental distraction effects, respectively. The present results show that phasic arousal and distraction follow distinct developmental trajectories. It seems thus crucial to take into account the impact of phasic arousal when investigating the development of distraction in future studies.

The number of missed and incorrect responses in attentional tasks is a sensitive measure of distraction since it was found to negatively correlate with school performance[78]. In presence of distracting sounds (irrespective of their timing), we observed a large increase of missed responses in the 6 and 7 year old children only. This detrimental distraction effect strongly decreases from age 6 to 7, and moderately from age 7 to 8. At 8 years old, the missed response rate reaches the adult level (similar with or without distracting sounds). An increase in missed response rate was previously seen in children of 5 and 6 years old in a no-distractor context[7]. In contrast, the missed response rate was not modulated by age in the CAT no-distractor trials, suggesting that the missed responses in 6 and 7 year olds is caused by the deleterious effect of the distracting sound. Additionally, the 11 and 12 year old children responded more to distractors than the 20 to 25 year olds. This increase in responses to the distractor suggests a higher impulsivity at this age which progressively decreases from 13 to 19 years old. A decrease in responses to irrelevant stimuli from 3 to 16 years old was previously observed[56–59]. Taken together, these results suggest that resistance to interference improves during childhood until late adolescence.

In the CAT, longer reaction times, target omission and responses to a distractor could result from either (i) an increased involuntary attentional capture, (ii) a reduced voluntary attentional inhibition of distracting sounds, or finally, (iii) an impossibility/difficulty to reorient the attentional focus back to the task at hand. Until now, few studies have investigated these hypotheses. Some electroencephalographic and behavioral works suggest that the increased behavioral distraction in children results from a delayed reorientation of attention to the task at hand[79,80]. However, inconsistent results have been reported[5] and further electro- or magnetoencephalographic studies during development will help understanding the brain mechanisms underlying increased distractibility.

In summary, distraction is increased in the youngest children (age 6 and 7) reflected by a large increase of missed responses and longer RTs after distractors. In the 11 and 12 year olds, distraction manifested as increased impulsivity, reflected in an increase in responses to distracting sounds. The combined use of reaction times, as well as missed and distractor response rates is necessary to assess the developmental trajectory of distraction and phasic arousal triggered by distracting sounds; this will help to fully understand the impact of distractors on behavior. Distraction is multifaceted and results in both attention and motor manifestations.

In broader models of behavioral control, the executive system coordinates the interaction of memory, attention and motor processes[2,46,81,82]. Motor control and attention are tightly linked: motor inhibition is driven by attentional selection, which is conditioned by past actions and their related memory traces. Difficulties in motor inhibition can result in responses to task-irrelevant events such as the distracting sounds or responses in anticipation of the targets, which can be considered as the behavioral expression of impulsivity. Many models have suggested a relationship between enhanced arousal level, impulsivity and motor control (e.g., Barratt & Patton, 1983; Eysenck & Eysenck, 1985). While the development of phasic arousal is poorly documented, impulsivity and motor control were found enhanced and reduced respectively in children[7,56–59].

While quite variable with age, the rate of anticipated responses is relatively stable between 7 and 12 year old and between 13 and 17 year old. It decreases first around 12-13 years old and around 17-18 years old. Increased impulsivity in children before the age of 12 has also been observed[7,8,83]. Participants made anticipated responses to the target only in presence of a distractor irrespective of age, suggesting that processes triggered by distractors influence the behavioral expression of anticipated responses. These anticipatory responses following distracting sounds could be driven by the phasic increase in arousal triggered by distractors or by reduced voluntary inhibitory motor processes.

We also noticed a progressive decrease in random response rate between 10 and 12 years old. As random response timing corresponds to a response which is believed to be independent from a stimulus, this response would then be related to a measure of motor – rather than attentional – control. Our findings suggest that motor control reaches its adult developmental stage around 13 years old. Beyond the assessment of attention capacities, the CAT also provides measures of impulsivity and motor control, which follow distinct developmental trajectories. Motor control and impulsivity display a significant improvement starting at 10 and 11-12 years old, respectively. Motor control reach an adult developmental stage around 13 years old, while impulsivity is found mature at 18 years of age.

To our knowledge, this is the first study to provide precise developmental trajectories of several attention capacities from childhood to adulthood. Voluntary orienting is functional at 6 years old, while sustained attention gradually develops from 8 to 13 years old. Interestingly, distraction manifests as omission of relevant stimuli in 6-7 year olds and as impulsivity in 11-12 year olds, when the reaction to distracting events seems to reach its mature adult expression. The maturation of distraction and voluntary attentional capacities is accompanied by a decrease in phasic arousal triggered by distractors from 8 to 13 years old, a reduced impulsivity at 12 and 17 years old and an improvement in motor control from 10 to 12 years old. These findings suggest that the attentional imbalance resulting in increased distractibility is rather related to reduced voluntary sustained attention capacities and enhanced distraction in children (6-8 years old), but to decreased motor control and increased impulsivity in teenagers (10-17 years old). In light of the present findings, psycho-education and classroom learning strategies would be improved by targeting attention processes in children and motor control capacities in young teenagers. As few normed neuropsychological tools are currently available to assess distractibility, these findings could help to better characterize attentional deficits and set up new individualized care for patients.

Methods

Participants.

409 subjects were included. Typically developing children from the 1st to 12th grade were recruited in public and private schools. Adults were recruited through flyers and email lists. Data from 57 participants were excluded from the analysis, either because of neurological disorders or substance use (N=9), auditory problems (N=2), non-compliance with the instructions (N=9), correct trial percentage < 50% in NoDis condition (N=13) or technical issues (N=24). A total of 352 subjects (88% right-handed, 51% female, 6 to 25 years old) were included in the analysis. All subjects had normal hearing and normal or corrected-to-normal vision. Participants were divided into 14 age groups (Table 1). This study was approved by participating schools and was conducted according to the Helsinki Declaration, Convention of the Council of Europe on Human Rights and Biomedicine, and the experimental paradigm was approved by the French ethics committee Comité de Protection de Personnes for testing in adults and children. For participants under age 18, signed informed consent was obtained from both parents, and assent was given by the children. All adult participants (18-25 years old) gave written informed consent.

Groups were matched for gender and handedness. Age groups from 6 to 17 years old were matched for economical status (SES, see Extended Data Fig. 3) and educational level (0 = no diploma, 1 = vocational certificate obtained after the 9th grade, 2 = high school diploma; 3 = 12th grade / associate's degree; 4 = bachelor degree; 5 = master degree and further). The 18 to 25 year old participants reported their own SES and education level: around 80% were students at the university and 20% were employees.

Stimuli and Task.

50 % of the trials (Fig. 1a) consisted of a visual cue (200-ms duration), followed after a 950-ms delay by a 200-ms target sound. The cue was presented centrally on a screen with a grey background and could either be a dog facing left or right, or a dog facing front. The target sound was the sound of a dog barking monaurally presented at 15 dB SL (around 43 dBA) in headphones.

In the other 50 % of the trials, the trial structure was identical, but a binaural distracting sound (300-ms duration) was played during the delay (Fig. 1b) at 35 dB SL (around 61 dBA). A total of 18 different distracting sounds were used (phone ring, clock-alarm, etc.) in each participant. The distracting sound could be equiprobably played at three different times during the delay: 200 ms (Dis1), 400 ms (Dis2) and 600 ms (Dis3) after cue offset.

The proportion of cue and target categories were distributed equiprobably between trials with and without distracting sound. The informative condition represented 75 % of the trials: in that case the dog was facing left or right, indicating the ear of the target sound presentation (37.5 % left and 37.5 % right). The uninformative condition represented 25 % of the trials: the facing-front dog was followed by the target sound in the left (12.5 %) or right (12.5 %) ear.

To compare behavioral responses to acoustically matched sounds, the same distracting sounds were played for each distractor condition (Dis1, Dis2 or Dis3) in the informative condition. Each distracting sound was played 4 times during the whole experiment, but no more than twice during each single block to limit habituation.

Subjects were instructed to perform a detection task by pressing a key as fast as possible when they heard the target sound. They were asked to focus their attention to the cued side in the case of informative cue. Participants were informed that informative cues were 100 % predictive and that a distracting sound could be sometimes played. In the absence of the visual cue, a blue fixation cross was presented at the center of the screen. Subjects were instructed to keep their eyes fixating on the cross.

When participants answered within 3300 ms after the target onset, a dog holding a bone (800-ms duration) was presented 500 ms after the response followed by the fixation cross for a randomized period of 1700ms to 1900ms. If the participant did not respond in time, the fixation cross was displayed on the screen for an additional randomized delay of 100 ms to 300 ms.

Procedure.

Participants were tested in small groups of 2 to 4. Adults were tested in the lab or at the university, and children were tested at school, all in a quiet room. Participants were seated in front of a laptop (approximately 50 cm from the screen) delivering pictures and sounds, as well as recording behavioral responses using Presentation software (Neurobehavioral Systems, Albany, CA, USA). Auditory stimuli were played in headphones.

First, the auditory threshold was determined for the target sound, in each ear, for each participant using the Bekesy tracking method. This resulted in an average target threshold across subjects of 28 ± 0.6 dBA (see Table 1 for details by age range). Then, participants performed a short training of the task followed by three 4-min blocks of 48 pseudo-randomize trials each. The order of the 3 blocks was randomized through participants using a Latin square. The experimenter gave verbal instructions to the children before the test. An experimental session lasted around 30 minutes. At the end of every experimental session, the experimenter explained the aim of the study to participants and took time to answer questions.

Adults and parents of children enrolled in the study filled out a short questionnaire about their SES characteristics and respectively completed the Adult Self-Report Scale (ASRS) [84] and the Attention-Deficit Hyperactivity Disorder Rating Scale IV (ADHD RS)[85] questionnaires, both assessing symptoms of ADHD in adults and children according to the diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders[86]. Adults also filled in the State-Trait Anxiety Inventory (STAI)Y-A and B[87] to evaluate anxiety as a state and trait. At the end, every participant answered a short post-experiment questionnaire about their motivation level, their focus state and stress level during the CAT.

Measurement parameters.

We used a custom MATLAB program to extract and preprocess behavioral data.

First, we visually inspected the reaction time distribution relative to target onset for each age (see Extended Data Fig. 4). For each participant, the longest reaction time for a correct response (RT upper limit) was calculated from all RT > 0ms using the John Tukey's method of leveraging the Interquartile Range. The shortest reaction time for a correct response (RT lower limit) was calculated for each age range (see Supplementary Information). Correct response rate corresponds to the percentage of responses with a reaction time (relative to target onset) superior or equal to RT lower limit and inferior or equal to RT upper limit.

The following 8 behavioral measures were analyzed further (see Extended Data Fig. 1):

- Median RT of positive RTs.
- Sustained attention (RT SD): mean standard deviation of RT > 0 in the NoDis condition for each block separately.
- Late response % (LateRep): the percentage of responses performed in the NoDis condition during the period starting from the RT upper-limit to 3300 ms.
- Missed response % (MissRep): the percentage of trials without any response made during the entire trial duration up to 3300 ms post-target.
- Cue response % (CueRep): the percentage of responses performed during the 150-450ms period post-cue onset.
- Distractor response % (DisRep): the percentage of responses performed during the 150-450 ms period post-distractor onset.
- Anticipated response % (AntRep): the percentage of responses performed:
  - in NoDis and Dis1: from 300 ms pre-target to the RT lower limit post-target;
  - in Dis2: from 150 ms pre-target to the RT lower limit post-target;
  - in Dis3: from 100 ms post-target to the RT lower limit post-target.
- Random responses % (RandRep): the percentage of responses performed in the remaining periods of the trials, i.e., within the 150 ms post-cue onset and:
  - in NoDis: during the 450 to 850 ms period post-cue onset;
  - in Dis1: during the 450 to 550 ms period post-cue onset;
  - in Dis2: during the 450 to 750 ms period post-cue onset;
  - in Dis3: during the 450 to 950 ms period post-cue onset.

Statistical analyses.

In order to estimate a degree of logical support or belief, Bayesian statistics were used. To estimate physical tendencies using complex models such as linear mixed error-component models (LME) or generalized linear mixed models (GLMM) were necessary, a frequentist approach was chosen.

<u>Socio-economic data analysis.</u>

To confirm that our sample population was uniformly distributed across age ranges in block order, handedness, and gender, we performed Bayesian contingency table tests. For children from 6 to 17 years old only, similar analysis was performed on SES and education level of the parents. We reported Bayes Factor (BF_{10}) as a relative measure of evidence. To interpret the strength of evidence in favor of the null model (uniform distribution), we considered a BF between 0.33 and 1 as weak evidence, a BF between 0.1 and 0.33 as positive evidence, a BF between 0.01 and 0.1 as strong evidence and a BF lower than 0.01 as a decisive evidence. Similarly, to interpret the strength of evidence against the null model, we considered a BF between 1 and 3 as weak evidence, a BF between 3 and 10 as positive evidence, a BF between 10 and 100 as strong evidence and a BF higher than 100 as a decisive evidence[88].

Bayesian statistics were performed using JASP® software (JASP Team (2018), JASP (Version 0.9) [Computer software]).

Statistical analysis of hearing threshold and attention scores are presented in Supplementary Information.

<u>Behavioral data analysis</u>.

Frequentist statistical approach.

A summary of the frequentist statistical analyses performed on behavioral data of the CAT can be found in Table 2.

When data provided an estimation of the intrinsic subject variability (several measurements by subject), we used linear LME. LME are the best way to deal with such datasets, as they allow for correction of systematic variability. We accounted for the heterogeneity of performances between-subjects and experimental conditions by defining them as effects with a random intercept, thus instructing the model to correct for any systematic differences between the subjects (between-individual variability) and condition (between-condition variability).

For binary data (LateRep, MissRep, CueRep, DisRep, AntRep, RandRep) we used GLMM. GLMM combines the characteristics of generalized linear models and LME; the regression model of GLMM is similar to LME except that it can handle a binomial distribution.

To confirm the need for mixed nested models for both LME and GLMM, we used a likelihood ratio analysis to test the model fit before and after sequential addition of random effects and covariates. We used the Akaike Information Criterion and the Bayesian Information Criterion as estimators of the quality of the statistical models generated for each behavioral type of measurement. We used the Wald T-test Chi-square (type II) to estimate the weight of the statistical parameters of the models and we only considered the explanatory variables. The fixed effect represents the mean effect across all subjects after correction of between-subjects and distractor conditions variability.

Frequentist models and statistics were performed in R® 3.4.1 using the lme4[89] and car[90] packages. We only considered results of main analyses significant at $p < .01$.

When we found significant main effect or interaction - and did not plan ahead for specific post-hoc analysis - HSD post-hoc tests were systematically performed using the emmeans package (emmeans version 1.3.2). P-values were considered as significant at $p < .05$ and were adjusted for the number of performed comparisons.

In the Results section, we systematically reported the SEM as the estimator of the distribution dispersion of the measures of interest.

Models.

On each type of behavioral measure (RT, RT SD, LateRep, MissRep, CueRep, DisRep, AntRep, RandRep), we analyzed the influence of four possible fixed effects (unless specified otherwise in the next section):

1) between-subject factor AGE: 14 levels (see Table 1);

2) between-subject factor GENDER: 2 levels (male and female);

3) within-subject factor CUE / CUELRN: 2 levels (CUE: informative vs. uninformative) for measures recorded after the target onset (Hit, LateRep and MissRep) and 3 levels (CUELRN: left, right and neutral) for the measures recorded before the target onset (CueRep, RandRep, DisRep and AntRep);

4) within-subject factor DISTRACTOR: 4 levels (NoDis, Dis1, Dis2 and Dis3), except for DisRep: 3 levels (Dis1, Dis2 and Dis3);

Median Reaction Times.

Participants with less than 50 % of the total trials with a positive RT in Dis1, Dis2 and/or Dis3 were excluded from median RT analysis. Based on visual inspection of median RT distribution in distractor conditions, one outlier was also identified and removed from this analysis. Revised samples for median RT analysis are: 6 year olds: n = 17; 7 year olds: n = 20). The percentage of missing data over the total sample of included subjects in analyses is shown in Table 2.

Before applying the LME, raw RT were log-transformed at the single trial scale to enable the prediction of relative changes in RT between factors.

For post-hoc analysis of the DISTRACTOR*AGE interaction on median RT, we planned to analyze two specific measures of the distractor effect: the distractor occurrence (median RT > 0 in NoDis minus median RT > 0 in Dis1) and the distractor position (median RT > 0 in Dis3 minus median RT > 0 in Dis1). Based on previous results[40,48], these differences can be respectively considered as a measure of the facilitation effect triggered by distracting sounds and a good approximation of the detrimental distraction effect. We first performed Shapiro tests to estimate the normality of the distractor occurrence and position measures. Planned non-parametric Kruskal-Wallis tests with the AGE as between-subject factor were applied to these measures when the data were not normally distributed. When the Kruskal-Wallis test revealed a significant effect of the AGE, we performed non-parametric paired Nemenyi post-hoc tests to identify developmental stages across age ranges.

Other measures.

RT SD was analyzed with the fixed factors AGE and GENDER as between-subject factor and BLOCK (3 levels) as within subject factor.

Response types were process as binomial data without transformation to enable prediction of absolute changes in response types between factors.

LateRep were analyzed in the NoDis condition, only, since few participants committed LateRep in distractor conditions (total average: 3.5 ± 0.1%).

Because of the important differences in the duration of the AntRep windows between distractor conditions (see Extended Data Fig. 4), the GLMM was performed on the NoDis and Dis1 conditions, only.

As all participants made in average less than 1 % of CueRep and RandRep, their modelization were limited to two-way interactions.

Planned Bayesian regressions.

Planned Bayesian Kendall regressions with age were performed on specific RT indexes of attention:

1. Voluntary attention orienting: ($medianRT_{NoDisUninf}$ – $medianRT_{NoDisInf}$) / $medianRT_{All}$;
2. Arousal effect: ($medianRT_{NoDis}$ – $medianRT_{Dis1}$) / $medianRT_{All}$;
3. Distraction effect: Voluntary attention orienting: ($medianRT_{Dis3}$ – $medianRT_{Dis1}$) / $medianRT_{All}$.

Data availability

The data that support the findings of this study are available from the corresponding author on request.

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Author contributions

R.S.H. and A.B.C. designed and conducted the study, performed data analysis and wrote the manuscript. J.H. contributed to data collection. H.E. and R.B. contributed to program development and statistical analysis. H.E. contributed to proofreading of the manuscript.

Competing interests

The authors declare no competing interests.