



Adaptation to high-frequency vibrotactile stimulations fails to affect the clock in young children

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ABSTRACT

Being able to estimate time precisely is fundamental to interact with the environment, and it is startling how our ability to track temporal intervals is prone to distortion. Unsurprisingly, researchers have studied temporal distortions extensively. Within the internal clock model framework, they have been often accounted for a change in the pacemaker's speed. However, only a few studies have tested whether these changes are eligible in children, investigating temporal distortions mainly via classical temporal bisection (in which participants should compare temporal stimuli with previously memorized durations). Since both temporal and non-specific, higher level factors mediate performance in such tasks, we decided to test time distortions in children by using a more low-level, perceptual design. Using a discrimination task and adaptation to high and low frequency vibrotactile stimulations, we compared haptic duration aftereffects in both young children (from 6 to 10 years of age) and adults. We found that sensory adaptation did not affect perceived duration in children up to 10 years of age, leading to an overall more rigid temporal representation among children who were younger. While adaptation to high frequency vibrotactile stimulations distorted perceived duration in both adults and 10 year-old children, younger participants did not experience change in perceived duration following adaptation. Conversely, adaptation to low frequency vibrotactile stimulations did not change the tested groups' perceived duration. Given the lack of temporal distortions to high frequency stimulations after adaptation in younger children, our results advocate for a different clock functioning. This suggests the internal clock functioning changes during development.

1. Introduction

No human activities could develop without their corresponding temporal dimension: from talking with someone to reading a scientific paper, or from anticipating the 'go' signal at the traffic light to planning one's next holiday. The entirety of human existence is undeniably bound to the passage of time and its organization within one's mind. Biological systems can track time across different scales (Buonomano, 2007), from microseconds to years. Even though researchers have successfully explored most of the mechanisms behind temporal perception (Buhusi and Meck, 2005; Overholt et al., 1992; Reppert and Weaver, 2001; Skottun, 1998), there are few clues about how the human brain encodes temporal information within the milliseconds-to-second range. Importantly, it is within this range that the low-level perception of the world is built and refined. Indeed, across this scale, most animals decode the temporal structure of auditory stimuli (Doupe and Kuhl, 1999; Tallal, 1994), perceive visual motion

(Johansson, 1976), anticipate events (Jazayeri and Shadlen, 2010), and coordinate their motor activity (Ivry and Spencer, 2004).

Researchers have developed many models over the years in an attempt to conceptualize how the brain encodes temporal intervals within the sub-second range. One of the earliest and most impactful models is the Internal Clock Model (Treisman, 1963), which defined a specific supra-modal circuit through which human beings can track time.

Even though psychophysical evidence has challenged the idea of a supra-modal, generalized clock lately (Anobile et al., 2019; Ayhan et al., 2009; Burr et al., 2007; Johnston et al., 2006), most of the models proposed in the recent years still included similarities with an internal clock mechanism to explain temporal perception (Church, 2003; Zakay and Block, 1995), though there are a few sporadic exceptions (Buonomano and Maass, 2009; Machado et al., 2009).

Given these models, researchers have studied temporal perception in adults using various paradigms (Allan, and Gibbon, 1991; Eagleman, 2005, 2008; Rose and Summers, 1995; Tomassini et al., 2012;

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Xuan et al., 2007). These paradigms have focused, among other things, on the theoretical modifications of the pacemaker's pulse rate to account for induced time distortions (Droit-Volet and Gil, 2009; Fetterman and Killeen, 1991; Kanai et al., 2006; Ulrich et al., 2006). However, studies have shown little interest in applying temporal information processing models in children, leaving a fundamental question: are temporal information processing models the same throughout the life span?

In one of the few studies investigating the pace changes at the clock level during the early stages of life, Droit-Volet and Wearden found that the internal clock sped up in children beginning at three years of age (Droit-Volet and Wearden, 2002). In their work, the authors demonstrated that a visual target's subjective duration increases if a visual flicker precedes the stimulus. At the same time, there is no change if a static white circle precedes the visual target. These findings support the idea that the internal pacemaker undergoes the same principle of functioning regardless of participants' age, producing a temporal dilation even in the youngest group of children. Droit-Volet further strengthens the hypothesis that clock behavior does not change across one's lifespan (Droit-Volet, 2017). Her work investigated the presentation of a series of auditory clicks that impact the perceived duration of visual targets. Even then, the author found a temporal dilatation of visual stimuli in both adults and children, highlighting that time dilation effects are a robust clock property.

To the best of our knowledge, these are the only two studies accounting for clock pace changes in children. Moreover, these two studies investigated clock acceleration properties using only one paradigm: the temporal bisection task (Droit-Volet, 2017; Droit-Volet and Wearden, 2002). We do not argue against the validity of this task in describing temporal perception properties, as it has been extensively used in both animals (Church and Deluty, 1977; Gibbon, 1977) and humans (Kopeck and Brody, 2010; Wearden and Ferrara, 1996; Wiener et al., 2014); it has also seen use in alternative versions reducing cognitive loads (Amadeo et al., 2019; Gori et al., 2012). However, we wanted to investigate whether it was possible to elicit temporal distortions in children with a perceptual paradigm that excludes attentional and cognitive factors known to impact the duration measurement (Block and Gruber, 2014; Poynter, 1989; Tse et al., 2004). We therefore decided to investigate temporal distortion using a relative, low-level perceptual design (a discrimination task), and sensory adaptation to elicit an increase in perceived duration. For our experimental design, we adjusted a previous paradigm that Watanabe and colleagues developed as a way to test tactile duration aftereffects among adults (Watanabe et al., 2010).

We expect that, if the pacemaker's acceleration property is a consistent feature of the clock during development, one would find a temporal aftereffect regardless of the age group tested or the task used. Instead, if the modifications at the clock level in previous research also reflect the involvement of non-specific factors (i.e., arousal, attention, or memory), younger children should not show any aftereffect in a pure perceptual task. If that were the case, we may suggest that the internal clock functions differently during development.

2. Materials and Methods

2.1. Participants

A total of 82 participants were recruited for this study. Participants were divided into six groups based on their age (6, 7, 8, 9, 10 y.o and Adults). A detailed description of the group's composition, including the mean and standard deviation of the ages, is reported in Table 1. Adults were recruited via Italian Institute of Technology mailing list, while children were recruited from two local primary schools in Genova. Data collection was done at the Italian Institute of Technology (Genova), in a quiet and dimly lit room. All participants reported normal tactile perception and no history of neurological disease and/or learning disabilities. Testing procedures were performed in compliance with the ethics committee of the local health service (Comitato Etico, ASL 3

Table 1

Summary showing number of participants in each age group, together with gender distribution, the mean and standard deviation of age. Within brackets we reported the number of initial participants, with their related statistics. Outside brackets we reported the number of participants that were included in the final analysis, with their relative statistics. In the lower part of the table, we reported the same indices considering the participants who completed the baseline and at least one of the two adaptation conditions.

Age Group	n	F	Mean Age	Standard Deviation
Six	10 (15)	3 (2)	6.602 (6.577)	0.265 (0.286)
Seven	11 (16)	6 (8)	7.467 (7.42)	0.31 (0.292)
Eight	8 (14)	4 (5)	8.41 (8.332)	0.254 (0.184)
Nine	7 (8)	2 (2)	9.39 (9.341)	0.248 (0.267)
Ten	15 (16)	10 (10)	10.492 (10.526)	0.419 (0.426)
Adults	13 (13)	7 (7)	27.923 (27.923)	9.887 (9.887)
High-frequency Adaptation				
Age Group	n	F	Mean Age	Standard Deviation
Six	8	2	6.681	0.239
Seven	11	6	7.366	0.284
Eight	7	4	8.3	0.15
Nine	7	2	9.39	0.248
Ten	15	10	10.492	0.419
Adults	13	7	27.923	9.887
Low-frequency Adaptation				
Age Group	N	F	Mean Age	Standard Deviation
Six	8	2	6.534	0.25
Seven	11	6	7.467	0.31
Eight	7	4	8325	0.092
Nine	7	2	9.39	0.248
Ten	14	10	10.539	0.393
Adults	13	7	27.923	9.887

Genovese, Italy) and the declaration of Helsinki. All adult participants and the legal representatives of the children gave written informed consent before the experiment.

2.2. Materials and Procedure

Participants sat in front of a wooden chamber built in-house. They were asked to put their hands inside it for the whole duration of the experiment. Inside the box, two vibrators were placed at 20° apart, and vibrotactile stimulations were delivered using a pin placed on top of each vibrator.

Vibrators were D-frame solenoids with 7 mm of maximum plunger length (general dimension of the solenoid: 30 × 16 × 19 mm), linked via USB cable by the computer used to run the experimental code. The connection between vibrators and the pilot computer was powered through a dedicated interface (Host), one for each vibrator. Experimental code was run in Matlab_R2019B, which was also used to generate all stimuli during the whole procedure and to collect responses. Input response was inserted by the experimenter, so that participants did not have to move the hands from the wooden chamber.

Participants sat precisely in between the vibrators, with their indices placed on top of each pin. Using this setup, participants could not see their hands as the chamber's upper panel occluded the sight. We decided to study the tactile modality instead of the more canonical visual modality because, in visual adaptation paradigms, participants must maintain fixation on a single point for a long time. Given the age of the youngest children recruited in this study, we thought that this was a difficult task, and results might be affected by the inability to keep the gaze on the fixation point.

The experiment was divided into three different experimental conditions: a Baseline condition, a high-frequency adaptation condition and a low-frequency adaptation condition. Participants were tested using a discrimination task, in which they had to discriminate between the duration of two sequentially presented vibrotactile stimulations,

to evaluate perceptual shifts. The reference stimulus was a vibrotactile stimulation with a fixed duration of 1 s, while the duration of the test stimulus changed across trials through an adaptive QUEST algorithm (Watson and Pelli, 1983) ranging from a minimum of 0.5 to a maximum of 2 s. The reference stimulus was always presented at the tip of the left index. The test stimulus was always presented at the tip of the right index. In each experimental condition, the two stimuli were separated by a 1 s Inter-Stimulus Interval (ISI). Since the temporal frequency of a stimulation influences its perceived duration (Kanai et al., 2006), we balanced it following a similar procedure used in previous research (Burr et al., 2011). The perceived temporal frequency of the stimuli was thus fixed at 10 Hz.

In the Baseline condition, the test and the reference stimuli were presented subsequently in a randomized order across trials, and only after the presentation of the second stimulus participants had to indicate verbally which one of the two stimuli lasted longer. After the experimenter had registered the response on the computer, the next trial started.

Differently from the Baseline, in the two adaptation conditions (low- and high-frequency) a sustained vibrotactile stimulation (i.e. the adapter) was delivered at the beginning of each trial before the presentation of the test and the reference stimuli. The adapter lasted 6 s and changed its frequency according to the condition. In the high-frequency adaptation condition, the adapter's temporal frequency was 20 Hz, corresponding to twice the reference's physical temporal frequency. In the low-frequency adaptation condition, the adapter's temporal frequency was 5 Hz, corresponding to half the reference's physical temporal frequency. One second after adaptation ended, the test and reference stimuli were presented.

Adult participants performed on average 155 trials (65 in the Baseline condition, 45 in each adaptation condition) while children performed 100 trials (40 in the Baseline condition, 30 in each adaptation condition). The whole experiment lasted approximately one hour, and data were collected on two different days to avoid any possible overlap of adaptation effects. The order of conditions was randomized across participants.

2.3. Data Analysis

To evaluate the performance of participants in each condition, we fit the following psychometric function into individual data:

$$p(t > r) = \frac{1}{1 + e^{-\frac{t-\mu}{\sigma}}}$$

The result of the fit is a sigmoid function that ranges from 0 to 1. This function shows the probability that the participant indicates the test stimulus as the one with a higher duration. This probability is expressed as a function of the physical duration of the test itself. The μ and the σ of the fit indicate the accuracy and the precision (respectively) of the participant's performance. Accuracy is represented by the Point of Subjective Equality (PSE), which is the duration the test must have so that is perceived as equal as the reference. The precision is represented by the Just Noticeable Difference (JND), which is the minimum change in duration needed to perceive the test and the reference as different at least half of the times. If temporal perception is shaped by adaptation at all ages, we would expect a change in the accuracy but no change in precision independently from participant's age. Indeed, the ability to discriminate the stimuli should remain constant regardless of the presence of the adapter.

To gauge the effect of adaptation, we evaluated the Magnitude of Adaptation (MoA). MoA is the difference between the PSE in one of the two adaptation condition and the Baseline condition, normalized by Baseline and expressed as a percentage. MoA's formula is the following:

$$MoA = \frac{PSE_{adaptation} - PSE_{baseline}}{PSE_{baseline}} \%$$

This parameter considers any difference between the Baseline condition and the adaptation conditions, and, since the Baseline weights every

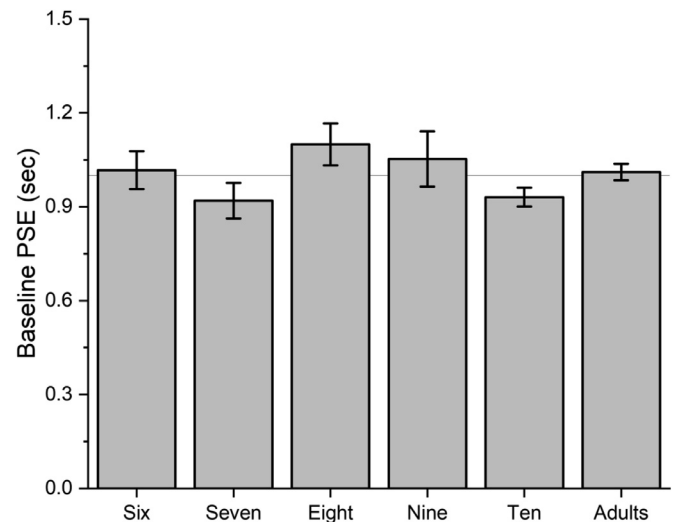


Fig. 1. PSE values in the Baseline condition for all age groups. Since no statistically significant difference between PSE values was found at the baseline level, we assume that even younger children were able to discriminate the two vibrotactile stimulations correctly. Error bars indicate \pm SEM.

measurement, it evaluates the effective temporal discrimination ability of the participants. A MoA value higher than 0 indicates a compression, while a MoA value lower than 0 indicates an expansion of the perceived duration of the test stimulus. If the MoA value is not statistically different from 0 in a significant way, no effect of adaptation is present.

3. Results

All the statistical analyses were computed using the R software ('lmer' and 'lme4' packages). To compare participants' performances, we evaluated the PSE and the JND within every experimental condition. In the analysis, we included only the participants able to successfully finish at least the baseline condition and one of the two adaptation conditions. We excluded participants whose performance was not evaluable (such as in the case the psychometric function did not fit). We also excluded participants whose JND was higher than the maximum difference achievable between the test and the reference stimuli (i.e., participants who had a JND higher than 1 s). Then, we checked for outliers across the baseline condition using Tukey's fences method, considering the whole data sample. Thus, we included 64 participants within the final analysis (see Table 1 for further details). The resulting sample was tested for normality (Shapiro-Wilk test, $W(63)=0.76$, $p=0.246$) and homogeneity of variance between the three conditions (Bartlett's Test, $T(2)=4.905$, $p=0.08$).

We first ran a One-Way ANOVA with factor Age (6, 7, 8, 9, 10 y.o. and Adults) on the PSE in the baseline condition to evaluate whether all the age groups were able to perform the task and correctly distinguish tactile stimulations via discrimination. We found no effect of age in the baseline condition ($F(5,58)=1.803$, $p=0.126$, $\eta^2=0.134$), thus confirming there was no difference between age groups in discriminating the tactile stimulations (Fig. 1).

Then, we ran a two-ways 3×6 mixed design permutation ANOVA with factors Age (6, 7, 8, 9, 10 y.o. and Adults) and Condition (Baseline, high-frequency adaptation and low-frequency adaptation) on PSE values. We used a permutation test with 10,000 repetitions to compensate for missing observations. Our analysis highlighted a significant effect of Age ($F(5,164)=3.101$, $p=0.008$, $\eta^2=0.075$) but no significant effect of Condition ($F(2,164)=1.303$, $p=0.242$, $\eta^2=0.027$) nor of the interaction between factors ($F(10,164)=1.285$, $p=0.22$, $\eta^2=0.065$) were found. The absence of interaction, the significant main effect of age and the general lack of effect for low-frequency adaptation in adults

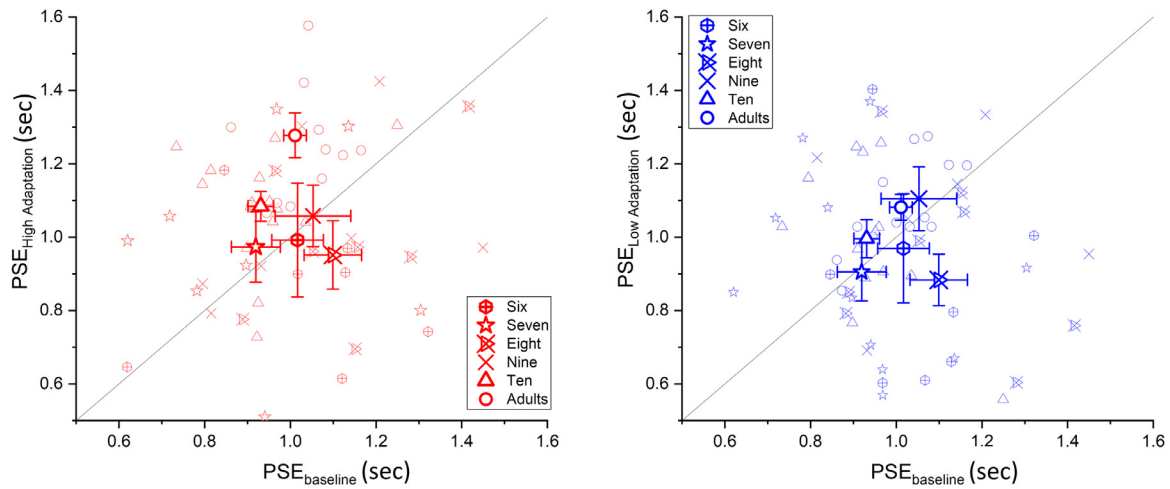


Fig. 2. PSE values for individual subjects in the high (red symbols) and low (blue symbols) frequency adaptation conditions, plotted against the PSE in the baseline condition. Bold symbols indicate results for data averaged across all age groups. Error bars indicate \pm SEM.

(Johnston et al., 2006; Watanabe et al., 2010), suggest that high-frequency adaptation to tactile stimulations might distort temporal perception at some age and that, however, it fails to distort it at some others (Fig. 2).

To deeper investigate the development of duration aftereffects, we ran a statistical analysis over MoA effects in each adaptation condition. Moreover, we considered the two adaptation aftereffects separately since, in adults, adaptation to low-frequency stimulations does not distort time perception (Johnston et al., 2006; Watanabe et al., 2010). We thus ran two nested one-way ANOVAs with factor group (6, 7, 8, 9, 10 y.o. and Adults) on MoAs, one for each level of adaptation. We used a nested model to compare the means of MoA across all the groups and, simultaneously, against 0. With this analysis, we could assess whether each group's means were different among them and if at least one mean differed from 0, i.e. at which age adaptation induced any aftereffect.

As expected, we found no differences in MoAs between age groups after low-frequency adaptation ($F(6,54)=0.384, p=0.886, \eta^2=0.04$), meaning that, after adapting to low-frequency vibrotactile stimulations, at all ages MoA was around 0. These results are in line with similar findings observed in adult participants, in which adaptation to low-frequency stimulations did not distort perceived duration (Johnston et al., 2006; Watanabe et al., 2010). Differently from low-frequency adaptation, we found an influence of age's participants on MoA values after high-frequency adaptation ($F(6,52)=3.03, p=0.013, \eta^2=0.26$). As post-hoc analysis, we then compared the MoA values of different age groups against 0 using one sample two-tails *t*-test to characterize the differences (correcting all *p*-value for Holm-Bonferroni multiple comparisons). Our results show that the MoA was significantly different from 0 only in the 10 years old group ($t(14)=3.032, p=0.044, 95\% \text{ CI } [5.29, 30.87]$) and in adults ($t(12)=3.457, p=0.028, 95\% \text{ CI } [0.103, 0.453]$). Indeed, in the 6 ($t(7)=0.096, p=1, 95\% \text{ CI } [-0.396, 0.431]$), 7 ($t(10)=0.576, p=1, 95\% \text{ CI } [-0.209, 0.354]$), 8 ($t(6)=-2.738, p=0.135, 95\% \text{ CI } [-28.07 - 1.58]$), and in the 9 years old group ($t(6)=0.484, p=1, 95\% \text{ CI } [-0.133, 0.201]$) MoAs did not differ from 0 in a statistically significant way (Fig. 3).

To evaluate the possibility that our data could be explained by a shift in precision, rather than accuracy, we ran a two ways 3×6 mixed-design ANOVA on JNDs. We considered factors Condition (Baseline, high-frequency adaptation and low-frequency adaptation) and Age (6, 7, 8, 9, 10 y.o and Adults). Even in this case, we randomly resampled data with no replacement (number of repetitions, $n=10,000$) to compensate for missing observations. Our analysis highlighted a main effect of Age ($F(5,164)=11.861, p<0.001, \eta^2=0.24$), while no main effect of Condition ($F(2,164)=0.202, p=0.667, \eta^2=0.0001$) nor

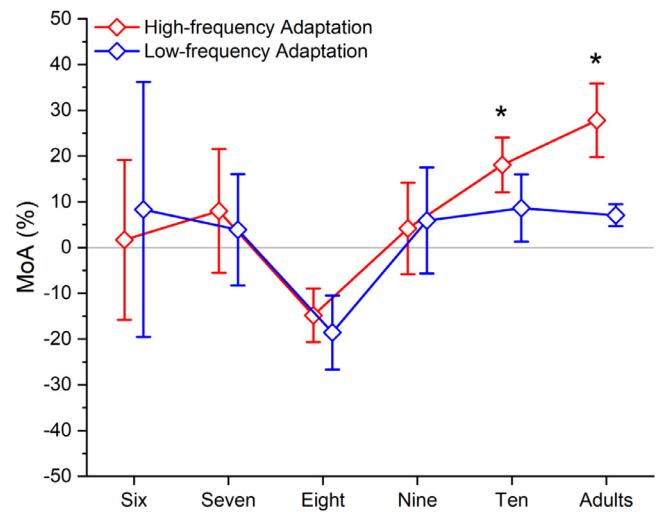


Fig. 3. Magnitude of Adaptation in both experimental conditions, grouped by age. The gray line represents a MoA of 0, when adaptation aftereffects are null and do not influence the perceived duration of the target. A MoA value lower than 0 indicates an expansion of the perceived duration, while a MoA value higher than 0 indicates compression of the perceived duration of the test. As we can appreciate, adaptation to low-frequency vibrotactile stimulations (blue line and symbols) had no effect on the perceived duration of the test stimulus, regardless of the age of the participants. Conversely, adaptation to high-frequency vibrotactile stimulations (red line and symbols) had no effect on children younger than 10 years of age, while it caused a significant compression of the perceived duration of the test in both the 10 years old and in the adults' group. Error bars indicate \pm SEM.

a Interaction effect ($F(10,164)=0.674, p=0.748, \eta^2=0.04$) were found. These findings are in line with previous literature (Droit-Volet et al., 2007), showing that younger children are generally less precise than adults in time discrimination tasks. However, given the absence of the main effect of condition and the Interaction effect, we can assume that adaptation did not impair their ability to discriminate the duration of the two-vibrotactile stimuli (Fig. 4).

4. Discussion

In the present study, we offer evidence that duration aftereffects change during the lifespan, being inconsistent in early life stages. In

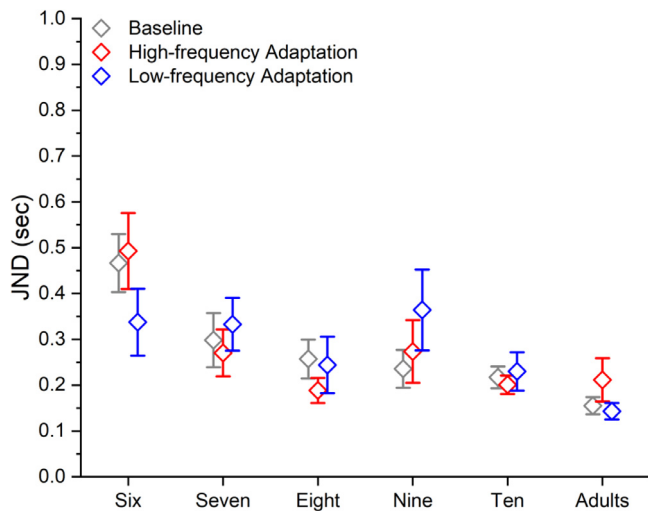


Fig. 4. Sensitivity measures across different conditions and age groups. Data showed here confirms that younger children are generally less sensitive in discriminating different temporal stimuli than older children and adults. Moreover, the presence of the adapter never impaired the ability to discriminate the duration of the vibrotactile stimuli, meaning that a reduced sensitivity cannot justify the difference in MoAs between age groups due to the adapting stimulation. Error bars indicate \pm SEM.

both children and adults, sensory adaptation to low-frequency tactile stimulations had no effect on the perceived duration of the stimulus presented shortly after. Conversely, adaptation to high-frequency vibrotactile stimulations compressed the perceived duration in both adults and 10 years old children, though it did not distort perceived duration in younger participants. Moreover, adaptation did not affect temporal precision in any of the groups; sensitivity shifts cannot account for any aftereffect being measured or failed to be measured.

At first glance, our results differ from the literature. Within a temporal information processing models framework, researchers have mostly explained temporal distortions while assuming a change of the pacemaker's speed was induced by a repeated stimulation presented before the timed event. This specific temporal modulation has been considered an inherent property of the clock, as researchers also found it in 3 year-old children (Droit-Volet and Wearden, 2002). Nonetheless, all previous works investigating time distortions in children used a temporal bisection task (Droit-Volet, 2017; Droit-Volet and Wearden, 2002). Even though this paradigm has seen extreme success when it comes to investigating how people generally perceive time, non-specific factors (i.e., attention and memory) are more involved in a temporal bisection task than in a purely perceptual paradigm, such as a discrimination task that the current study uses. Performance in a temporal bisection task is therefore potentially modulated not only by changes at the clock stage, but also by arousal modifications (Johnston, 2012) and, more importantly, higher executive functions (Droit-Volet and Hallez, 2019; Levy et al., 2015; Zakay, 1992). The results of the second study that investigated clock accelerations in children strengthen this concern (Droit-Volet, 2017). In that case, time distortions significantly correlated with children's cognitive abilities, such as attention and memory. Note that studies have also used clock models to explain the influence of attention on perceived duration (Taatgen et al., 2007), and that attended stimuli (Thomas and Weaver, 1975), or stimuli that require a higher allocation of exogenous attention to be processed (Tse et al., 2004), appear to last longer. Thereby, we think that task-related specificity may explain the different effects of prior repeated stimulations over perceived duration.

Furthermore, developmental differences in time perception have been often explained considering changes at the cognitive level, assuming that the maturation of general, high-level cognitive processes mediate developmental improvement rather than timing dedicated neu-

ral substrates (Droit-Volet et al., 2007; Zélanti and Droit-Volet, 2011). Here, we partially challenge this assumption, suggesting that pure temporal mechanisms operate differently during early life stages. Our findings, combined with our experimental design, minimize the impact of attentional components over duration judgements. Notably, adaptation to low-frequency stimulations does not affect perceived duration in adults (Johnston et al., 2006; Watanabe et al., 2010), so that perhaps we cannot associate time distortions induced by sensory adaptation with attentional orientation due to the adapter's presence. We propose that the clock functioning might be different at different developmental stages in light of these considerations and our findings. Our results suggest that pure timing neural mechanisms undergo developmental changes that are independent of the maturation of high cognitive processes. Given this, the absence of duration aftereffects in younger children is explainable by their inability to modulate the clock after repeated stimulation, supporting a number of assumptions. First, changes in perceived duration using a discrimination task are unlikely to reflect the influence of high-level cognitive mechanisms. Second, when the influence of high-level cognitive processes reduces, one can observe different temporal behaviours in children and adults. While the latter experience spatially localized distortions of perceived duration after adaptation, younger children maintain a veridical temporal representation. Third, even though various separated neural mechanisms likely mediate time perception (Eagleman, 2008; Pariyadath and Eagleman, 2007), they develop at different paces. Thus, when singularly investigated in young children, they produce completely different outcomes.

Why do younger children experience no duration aftereffect after the exposure to high-frequency adapters? We speculate that, during development, perceptual systems must represent the environment in the most reliable way to enhance cross-sensory calibration mechanisms. While Ernst and Banks demonstrated that adults integrate information through different sensory modalities in a statistically optimal fashion (Ernst and Banks, 2002), Gori and colleagues determined that children do not integrate multisensory information in the same optimal way (Gori et al., 2008). Moreover, substantial evidence supports the fact that the absence of multisensory integration in young children may reflect the cross-sensory calibration process (Gori et al., 2010). This theory states that the most specialized sense trains the others to perceive specific features (e.g., vision 'teaches' touch to discriminate orientation, while touch 'teaches' vision to discriminate size). In other words, during development these calibration mechanisms may lead to the necessity of having stable perceptual representations of external objects' characteristics. If the perception in children was easily distorted through sensory adaptation, cross-sensory calibration mechanisms could be twisted by adaptation aftereffects. It is therefore conceivable that, to avoid flaws in cross-sensory calibration processes, neural mechanisms that distort perception are attenuated throughout childhood. As soon as these processes consolidate, perceptual systems increase their flexibility and, consequently, expand their response windows.

Our study demonstrated that children younger than 10 years of age do not systematically experience canonical duration aftereffects, at least in the haptic modality. Our results support the idea that clock components might act differently in young children (Wearden, 2016), and that different behaviors only emerge when there is a reduction in the influence of high cognitive processes. We offer evidence that non-cognitive mechanisms that selectively mature during growth may mediate temporal processing during development. Indeed, our work pointed out differences in temporal behavior between younger children and adults that could have went unnoticed during investigation of duration aftereffects.

4.1. Limitations of the Study and Future Directions

This study offers evidence that the clock might operate differently in children and adults. This difference supports the hypothesis that one perceives time through a cluster of neural mechanisms that

cooperate and develop at different paces. One can selectively investigate them through different paradigms with the intention of including or excluding specific neural components (i.e., attention or memory).

Nonetheless, our work is far from exhaustive in its purpose or results. First, we tested the development of duration aftereffects only in the tactile domain with the assumption that our findings were generalizable to sensory modalities. Investigating duration aftereffects in children via different sensory channels is fundamental to either support or challenge our results. Second, while behavioural experiments are precious to phenomenologically describe perception, they allow us to speculate about the neural substrates involved in certain physiological mechanisms. As a result, there is a need for further studies involving electrophysiological and neuroimaging techniques if we are to comprehend the neuro-anatomical basis of time perception, including the clock. In this regard, we are confident that the absence of duration aftereffects in younger children will help future researchers target more specific cortical and subcortical structures.

Declaration of Competing Interest

The author declares no conflicts of interest of relevance to this topic.

Authors contribution

ND, AT and MG designed the study. ND performed data collection and data analysis. ND wrote the first draft of the manuscript. All authors participated in making revision and approved the final version of the manuscript.

Data and Code Availability Statement

The code developed and the data that support the findings of this study are available from the corresponding author upon reasonable request.

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