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DEVELOPMENTAL AND AGING ASPECTS OF TIME ESTIMATION

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Abstract

Through the course of life, humans experience age-related alterations in the way they perceive time. Along with these changes, cognitive processes such as attention and memory are constantly being modified through experience, neural development, and healthy-aging. To-date, however, little is known about the different developmental and aging aspects of timing percepts and their association with cognitive mechanisms. The aim of this study, therefore, was to investigate interval discrimination and reproduction in relation to cognitive processes by comparing individuals in different points in lifetime. In order to accomplice this, 3 different age groups (13-15, 20-22, 49-51 years of age) were selected. Using identical paradigms and stimuli in all age groups, we compared temporal estimation performance across groups and correlated findings on duration estimation with cognitive aspects of attention and working memory. Specifically, we utilized both reproduction and bisection tasks for visual and auditory signals in order to investigate timing, along with cognitive testing on Visual Search, Dual *n*-Back, and Vigilance. We found worse temporal accuracy and lower temporal sensitivity in terms of *Bisection Point* (*BP*), proportion of long responses and coefficient of variance (CV) in children as compared to young- and middle-age individuals, age effect in variability in reproduction task conditions. These profiles were highly correlated with the attentional and memory performance of the respective groups, while regression analyses showed that age along with the cognitive assessment scores could explain large proportion of variance of the timing scores. Attention in terms of accurate performance in the visual search task was the most significant predictor of temporal accuracy, even when we controlled for age. All in all, our results show more differences in the adolescents than in the middle aged group; these changes are suggested to be

due to cognitive changes during late childhood while time estimation in middle age seems relatively unchanged.

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List of Abbreviations

BP	Bisection point
JND	Just noticeable difference
MA	Middle-aged Adults
MI	Multisensory integration
ms	Milliseconds
OA	Older adults
POE	Point of objective equality
POS	Point of objective simultaneity
PSE	Point of subjective equality
PSS	Point of subjective simultaneity
RT	Reaction time
SJ	Synchrony judgment
TBW	Temporal binding window
TOJ	Temporal order judgment
WR	Weber ratio
YA	Young Adults

Introduction

Timing, within a dynamic natural world, permeates both perception and movement, from viewing a video to the way we move our hand towards an object. Every event in the environment has a temporal dimension, so the mind has mechanisms for processing the temporal characteristics of these dynamic events (Droit-Volet, Fayolle, & Gil, 2016). Humans share this passage of time experience with animals, but this experience carries the characteristic of not relaying in one specific organ, a time-receptor. Nonetheless, the sense of time is subject to influences throughout the course of life, such as developmental and aging changes in interval judgments.

Extensive work has been done identifying the adult behavioural (e.g., Jazayeri & Shadlen, 2010; Wearden, Todd, & Jones, 2006) neurological (e.g., Meck, Penney, & Pouthas, 2008), and atypical (e.g., McGee et al., 2004; Wittmann et al., 2007) temporal judgment patterns; there have been results in the field of aging as an influencing parameter on the way humans judge time. Especially, when it comes to the seminal point of development between childhood and early adolescence, as well as, middle age, little has been done. During the last two decades researchers have carried out systematic studies on temporal behaviour in children (e.g., Clément & Droit-Volet, 2006; Droit-Volet et al., 2016; McCormack, Brown, Maylor, Darby, & Green, 1999), and older adults (e.g., Bedard & Barnett-Cowan, 2016; Lustig & Meck, 2001). Briefly, in developmental studies while children from the age of 3 to 10 can produce similar-to-adults results, they tend to be more variant in their responses (Droit-Volet et al., 2016). On the other hand, there are results in the older-adult's timing are few and contradictory as studies describe age-related impairments (e.g., Rammsayer, 2010), no effects (e.g., Baudouin, Vanneste, Pouthas, & Isingrini, 2006); Hancock & Rausch, 2010), or even more accurate performance in older than younger adults (Eisler & Eisler, 1994). In addition to this, only few studies have examined the changes across a wide range of the life-span in timing (Block, Zakay, & Hancock, 1999; Block, Zakay, & Hancock, 1998; McCormack, Brown, Maylor, Darby, & Green, 1999). There is an absence of data firstly, from more strictly controlled younger and older adult group ages, and secondly, about straight comparison of children with older groups. The present thesis aims in providing more direct evidence on the contrasts between development and aging points for temporal perception along with outlining relationships with cognitive components.

Examining our topic closer, studies on age-related changes in interval timing have a long history (e.g., Brackbill & Fitzgerald, 1972; Feifel, 1957; Pouthas, 1985). Findings reveal that internal clock mechanism is functional from very early ages of development (Droit-Volet, & Delgado, 2007). Interestingly, increase of proportion of long responses with increasing actual duration have been demonstrated, with behavioural and neuroimaging data, as early as infancy (Brannon, Suanda, & Libertus, 2007; Provasi, Rattat, & Droit-Volet, 2011). In addition this is consistent with studies from healthy young adults as well as animal studies (Malapani & Fairhurst, 2002; Meck et al., 2008). For example, in studies with bisection task, a temporal discrimination task, children's responses have provided psychophysical functions with proportion of long responses increasing with larger intervals (Droit-Volet, Clément, & Fayol, 2003; Droit-Volet & Wearden, 2002) as in human adults and animals. Most importantly, time discrimination precision increments have been reported through childhood, from 6 months to 10 years of age (Brannon et al., 2007; McCormack, Brown, Maylor, Darby, & Green, 1999; Zélanti & Droit-Volet, 2011). A study has also reported the ability of temporal generalization for supra- and infra-second duration in 3-, 5-, and 8- year olds. However, poorer temporal sensitivity and more variability in responses have been observed in childhood (Droit-Volet et al., 2006), meaning that children can estimate time correctly but their answers are less consistent that those of older ages.

Although the mechanisms involved in age-related changes in interval estimation are yet to be deciphered, healthy aging is generally characterized by faster passage of time. This notion is generally supported by reproduction studies, where participants are ask to reproduce a presented interval that report overproduction of intervals by older individuals (e.g., Perbal, Droit-Volet, Isingrini, & Pouthas, 2002; Rammsayer, 2001). With a reproduction task that compered responses of YA and elderly, Baudouin et al. (2006) showed that older participants were less accurate in the reproduction of the observed interval in the complex condition of their paradigm, that involved a parallel characterization of numbers as even or odd (dual-task condition). However, they reported similar-to-young results in the simple reproduction condition, where (Baudouin et al., 2006), while Anderson, Rueda, and Schmitter-Edgecombe (2014) demonstrated time estimation stability in healthy older adults -when compared to healthy younger adults- with no variations in their judgment during a year of multiple testing. Moreover, an aging study including multiple age groups with middle- and older-aged adults show no difference between groups in absolute constant error and absolute error of the production of short intervals (Hancock & Rausch, 2010). As mentioned before, existing studies examining the changes across a wide range of the life-span in timing are few (e.g. McCormack, Brown, Maylor, Darby, & Green, 1999). In addition, for the comparison of children with older groups, there are mainly meta-analytic reviews (Block et al, 1999; Block et al., 1998), comparing mostly different tasks that these age groups completed in different studies. Generally, there is lack of data from strictly controlled age ranges when studies incorporate individuals in their adulthood - Droit-Volet and colleagues (e.g. Droit-Volet et al., 2018; 2016; 2013) have used quiet short age ranges when exploring time estimation in children. For example, Baudouin et al., (2006), to compare between young and old adults, used individuals aged 20–35 and 60–81, which are large and unequal ranges; it is worth mentioning that Hancock and Rausch (2010) incorporated well controlled ranges but only for adult individuals.

Comparisons between different life-span points are, moreover, important because development and aging are being accompanied by basic cognitive abilities changes, besides time judgment differences. In early childhood the emergence of working memory and its increment throughout childhood and adolescence been observed until adulthood (Østby, Tamnes, Fjell, & Walhovd, 2011; Tamnes et al., 2010). Furthermore, information processing, selective attention, spatial working memory and short-term memory, also increase with age until adulthood (Droit-Volet & Zélanti, 2013; López-Vicente et al., 2016; Luna, Garver, Urban, Lazar, & Sweeney, 2004). Importantly, response inhibition begins to reach adult-performance levels at the age of 14 while processing speed at 15 years old (Huizinga, Dolan, & van der Molen, 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

On the other hand, as we grow older, we suffer a decline in mental and physical fitness (Paraskevoudi, Balcı, & Vatakis, 2018). Decline in every sensory organ, as well as in central functions, is observed even in healthy aging: Liu and Yan (2007) have shown an increment in thresholds for auditory perception; a decline in visual acuity seems to also “accompany” healthy aging, (Gittings & Fozard, 1986; Kaido et al., 2011). Deterioration of executive functions, motor speed, working memory, and controlling of attention have been previously observed (Fabiani, 2012; Falkenstein, Yordanova, & Kolev, 2006; Kolev, Falkenstein, & Yordanova, 2006; Li, Gratton, Fabiani, & Knight, 2013; Morel, 2012). A gradual loss of brain volume, at about 0.5 per cent or more after the age of 60 years old has been reported thought a detailed review of longitudinal MRI studies (Hedman, van Haren, Schnack, Kahn, & Pol, 2012). In older age, reductions of function and speed of processing in prefrontal areas have been reported (Khanna, Rawat, & Tripathi, 2017; Lindenberger & Ghisletta, 2009) as well as changes in working memory components such as inhibiting irrelevant activity in a working memory task (Borella, Carretti, & Beni, 2008). These deteriorations can also have direct impact in controlling attention and performing neuropsychological test (Paraskevoudi et al., 2018). Lastly, studies have also shown age-related declines in neurotransmitter systems, especially in noradrenaline, dopamine, and serotonin, which might also lead to alterations in cognitive function (Karlsson, 2009; Keck & Lakoski, 2001).

Interval time in psychological view usually involves attention and memory, as attention may serve the role of moderating engagement in an event that temporally unfolds, which is then stored or compared with other events in memory. For example, duration perception has been found to be affected by attention engagement (e.g., Block, Hancock, & Zakay, 2016). Attention is one of the key factors in the attentional-gate model; this model describes temporal perception as modulated by an internal clock-mechanism consisted by a pacemaker emitting pulses at a specific rate, the attentional gate, which is modulating the number of pulses that will be transferred to the third component, the accumulator of the pacemaker pulses (Droit-Volet, 2013). The count of pulses accumulated is then being maintained in the short-term memory as well as to the reference system –holding information of past experiences with intervals. To reach a specific temporal conclusion, a comparison must be made between the presently accumulated pulses and the remembered ones (Broadway & Engle, 2011). The aforementioned results of interval judgments improvement in children are in accordance with the attentional-gate theory, as children seem to have the internal clock leading to somewhat correct time estimation, and their increasing sensitivity is due to changes in the components of this model (attentional modulation of the gate, storing and comparing the interval, etc.) (Droit-Volet, 2013). As the steepness of children's temporal discrimination increases with age, it has been suggested that this improvement in timing sensitivity might accord with other developmental cognitive abilities improvements (Allman, Teki, Griffiths, & Meck, 2014) such as improvement of attention or inhibition. Importantly, a study by Droit-Volet & Zélanti (2013) examined development-related changes in a number of cognitive functions (including selective attention short-term memory, working memory, and processing speed) in the form of neuropsychological tests and also temporal sensitivity. In the discrimination task used in the aforementioned study, time sensitivity for the short and the long durations was predicted by information processing speed, while working memory capacity identified as predictor of improvement but for smaller proportion of variance (Droit-Volet & Zélanti, 2013). Similarly, development-related improvement in temporal sensitivity has been associated specifically with attentional factors. In a study by Zélanti and Droit-Volet (2011), the Weber ratio –which increment reveals lower sensitivity –decreased with better performance in the attentional tasks.

As temporal processing relies on both peripheral organs and central -cognitive processes, subsequent changes in duration perception in healthy aging are expected and observed. Overproduction and increased magnitude of errors reported for older individuals are in line with predictions of attentional gate model of a slower pacemaker speed in older age, too (Anderson, Rueda, & Schmitter-Edgecombe, 2014). While some findings (e.g., Craik & Hay, 1999) have suggested that the role of cognitive load in temporal estimation differences between adults of older age more than younger adults, this was not evident in prospective temporal paradigms meta-analyses by Block, Hancock, and Zakay (2016).

Except age and cognitive influences, there are other influencing factors in the passage of time: Signal modality affects duration estimation despite being a non-temporal characteristic (Yue, Gao, Chen, & Wu, 2016). Audition events are temporally perceived differently from visual events (Wearden, Todd, & Jones, 2006), as auditory stimuli are judged more accurately and less variably than visual stimuli (Ortega, Lopez, & Church, 2009).

The perception of time duration for acoustic and visual stimuli has been studied extensively for each modality separately, mainly by using the reproduction and the bisection task. Although some findings on how we distinguish intervals by aural or visual signals are contradictory (Murai & Yotsumoto, 2016), literature has solidified the notion that auditory stimuli judged to be longer than visual ones (e.g., Berry, Li, Lin, & Lustig, 2014; Wearden, Todd, & Jones, 2006; Penney, Gibbon, & Meck, 2000). Cicchini et al. (2012) studied adult groups who had a different musical experience (percussion, string and non-musician individuals) in a reproduction and a discrimination paradigm, presenting participants either acoustic tones or visual flashes. They noticed that, although the percussion musicians generally had better performances in both the reproduction and discrimination than the rest of the groups, overall, the participants, regardless of musical experience, were more accurate in responding to acoustically presented intervals (Cicchini et al., 2012). Murai and Yotsumoto (2016) compared the perception of time intervals in acoustic and visual modality with similar experimental design using a reproduction and a bisection task. In particular, they asked participants to reproduce time intervals that were signalled by a sequence of either two tones or two shapes on the screen. Although the reproduction test resulted in a better discretion for the auditory condition compared to the visual condition, this did not apply to all participants. Moreover, Droit-Volet, Tourret, and Wearden (2004) examining temporal bisection in 5-and 8-year-olds and adults also found auditory stimulation to be perceived as longer than temporally-identical visual stimulation. Linking the modality role with age factors, it has been observed that increased temporal sensitivity with age occurs more quickly in audition stimulation than visual (Droit-Volet & Zélanti, 2012).

Consequently, it is still unclear whether the acoustic modality has a special role in timing (Ivry & Schlerf, 2008) and whether these differences are observed in development or later in life. And as literature on duration perception has not yet provided us with a clear explanation for differential results in timing between children, young and middle-aged adults, the present study is an attempt to outline the behavioural changes in seminal points of lifespan regarding duration perception and its relationship to cognitive factors.

Therefore, the purpose of this research is to examine whether the perception of duration in the general population is influenced by age and what are the specific differences of age groups in interval estimation. Additionally, we aimed to explore differential responses of age groups as a factor of stimulation characteristics such as modality. At the same time, the design aimed at exploring cognitive factors effect in all these timing results. We assumed that estimates for aural stimuli will be more accurate than visuals but are expected to be overestimated in all age groups. In the visual modality we expect variability to be more pronounced in children and middle-aged individuals. Based on the extensive previous results about the role of cognitive factors in interval estimation, we expected that not only age but cognitive performance would account for timing results in the regression models. Lastly, we hypothesized that middle aged and children’s group would have worse performance in the working memory and attention task, and this will be accompanied with sequential correlation of their cognitive performance with lower temporal sensitivity.

Method

Participants.

The total sample of our study consisted of 60 naïve individuals, 13-51 years old (M_{age}=28.22 years, SD_{age}=5.96, 39 females). Participants were divided into 3 groups aged: 13-15 (M_{age}=13.5 years, SD_{age}= 0.69, 12 females), 20-22 (M_{age}=21.4 years, SD_{age}= 0.68, 15 females), and 49-51 (M_{age}=49.75 years, SD_{age}= 0.91, 12 females). Each group was composed of 20 participants. All participants were native Greek speakers, did not report any history of neurological or mental disorder, and reported good overall health. Participants had normal or corrected-to-normal vision and normal hearing. For under-age participants, a guardian provided consent for participation at the beginning of the procedure.

Material and Apparatus

For the execution of all the experiments, 3 different laptops were used, with 15 to 17.3-inch screen size. The participants sat at a distance of about 55 centimeters away from the screen, while the visual stimuli appeared at the center of the screen. Auditory stimuli were presented via the laptops' speakers, with the volume adjusted to a participant-desired but appropriate level for conducting the experiment. Demographical data was acquired with the use of OpenSesame 2.9.7 software; while the rest of the data (time- and cognitive-related) were acquired with Presentation software; the stimuli for each test are being described below.

Procedure

All participants completed 4 tasks on duration perception, and 3 on cognitive processing, all presented in random order. Specifically, the tasks were a two-alternative forced choice

(2AFC) duration discrimination task (i.e., bisection task) for visual and auditory stimuli, a duration reproduction task for visual and auditory stimuli, and a visual search task (feature and conjunction search), n-back, and vigilance task (see Table 1).

All participants received the same instructions before each task. Participants were, also, explicitly told that they should respond as accurately as possible in the reproduction, and bisection, while they were told to respond as accurately and as quickly as possible during the cognitive tasks. The overall procedure lasted about an hour. Short breaks were provided after each task and block to allow some rest, especially for children. All participants were tested during daytime.

Table 1
Task category and conditions

Duration	Reproduction		Bisection		
	Visual	Auditory	Visual	Auditory	
Cognitive	*n*-back		Visual Search		Vigilance
	1-back	2-back	Conjunction	Feature	

Bisection Tasks. The temporal bisection task is used extensively to measure duration perception (Church & Deluty, 1977). Although encountered in variations, bisection usually consists of the following two phases: During the training phase, participants are familiarized with 2 referent intervals, the “prototype” short and the “prototype” long one, presented in the form of a sensory stimulation and so that the participant can be familiarized with the time scale of the experiment through repetitions. Individuals at this phase have to respond whether an interval is more similar to the short or to the long one and receive feedback, so they can distinguish long and short durations (Droit-Volet, 2010). In the second phase, participants observe different time intervals (usually within the time range of the prototype short and prototype long duration) and are asked if the durations are more similar to the original short or long duration, without receiving any feedback (Droit-Volet et al., 2016; Lustig & Meck, 2001).

Our participants were tested in similar visual and auditory bisection task; both consisted of familiarization and test phase. In the familiarization phase, participants were presented with a “short” and “long” duration (400 and 1600 ms, respectively) in the form of a large rectangular in the middle of the screen. After the initial exposure to the durations, participants were trained to press the “I” button to indicate that the stimulus was the “short” standard and the “A” button for the “long” standard, in eight trials (4 short and 4 long duration trials), presented in random order. During the training, a response resulted in the appearance of a feedback indicating the participant of the outcome of her choice (“Correct!” or “Wrong” in Greek). In the test phase, we used black and white circles (~2.1 cm in diameter) appearing in seven different durations (400, 600, 800, 1000, 1200, 1400, and 1600 ms), while no feedback was given.

For the auditory modality, the bisection task was identical to the visual one with the expectance of stimulation. Participants were presented “short” and “long” durations (400 and 1600ms) in the auditory modality, presented as low (300Hz) and high pitched (4500Hz) tones. Again after they were familiarized with the procedure and the durations, they completed the test phase. In the test phase of the auditory modality, we used the above mentioned high and low pitched tones appearing in seven probe-durations (400, 600, 800, 1000, 1200, 1400, and 1600 ms), this time no feedback was given. In both bisection tasks, there were 2 test blocks of 28 trials, with 4 trials for each duration within each block, resulting in 8 repetitions of each duration total. The trials within each block were presented in random order. Participants had to press the “I” button for short duration and the “A” button for the long duration.

Reproduction Tasks. One of the first tools used to investigate time perception mechanisms, the Temporal Reproduction Task, includes the presentation of intervals, in the form of stimuli, usually visual or acoustic (Droit-Volet, 2010). In this paradigm, the participant is asked to reproduce the experienced temporal length -after the end of a presentation of a sensory interval- by defining it with the continuous or instant pressing of a key (Lewis & Miall, 2009; Murai & Yotsumoto, 2016). Although, Cicchini, Arrighi, Cecchetti, Giusti, and Burr (2012) showed that the task has credible results, which, appear to be predicted by the Bayesian model used in the analysis, the control and the execution of the response motion during reproduction involve latency time added to the reproduced interval. Thus, the task has been argued to involve more cognitive and kinetic processes that affect the results in relation to a discrimination test, such as the bisection task mentioned above (Droit-Volet, 2010) According to Droit-Volet (2010), delay due to the preparation, execution of motor procedures and keystroke lead to unreliable differences between groups, especially when comparing typical young adults to clinical population, children or the elderly. However, it is important to use multiple tasks as a way to provide stronger support that a specific manipulation of a factor (e.g., in the present study, age) affects perceived timing differences, and results are not just bias-driven, a suggestion previously made for synchrony judgment (for usage of multiple tasks in the same participant for synchrony, see Linares & Holcombe , 2014).

In these tasks, participants had to evaluate the displayed duration of acoustic and visual stimuli. The reproduction task for the visual modality included a familiarization and a test phase. The task was to reproduce the duration of the visually presented series of letters appearing within a blue square. The letters alternated with random speed, varying from 200 to 600 ms; each trial began with a cue presentation, a cross, and after a delay the blue square and the letters appeared for a certain duration; in this sub-phase of the task, called the encoding phase (Pouthas & Perbal, 2004), a message appeared at the bottom of the display in Greek, informing participants to evaluate the duration of the blue square. Subsequently, the blue square was presented alone accompanied with the message that the participant should reproduce the previously presented duration, in the reproduction phase (Pouthas & Perbal, 2004; Perbal, Droit-Volet, Isingrini, & Pouthas, 2002). The participants then had to reproduce the perceived duration by waiting for the amount of time the perceived duration lasted and then press the ENTER button as soon as they perceived the presented interval had elapsed. In the familiarization phase, 8 trials with practice durations (2200 and 5200ms) appeared. The test phase included 2 blocks with 36 trials, which appeared randomly within each block, one for short durations (500, 800, 1000, and 1500 ms) and one for long durations (2200, 3200, 4200, and 5200 ms). In the auditory reproduction paradigm, the participants were asked to reproduce the duration of the aurally presented durations. Each trial began with a cue presentation, a cross, and followed by the sound to be reproduced. Participants were given the instruction that, after the sound was presented, she should wait as much as the perceived duration lasted and press the ENTER button immediately when this time has passed. Two blocks with 30 trials each for aural durations of 750, 1500, and 3000 ms, constituted this test, and appeared randomly within each block. After each block, a short break (monitored by the participant, and lasting 5–10 s) was provided to allow some rest. The stimuli were a series of 5 consonant and 5 dissonant sounds, resulting in 2 repetitions of a certain sound duration. In the beginning of each reproduction task, individuals instructed that they should not try to use strategies such as counting, hand or foot tapping to help them with estimating the passage of time.

***n*-back task.** In this experiment, the participants were required to monitor a series of visual and auditory stimuli appearing in the center of the screen and to respond whenever a given stimulus was the same as the one presented *n* trials previously (in this study, 1- or 2-back; Jaeggi, Buschkuehl, Perrig, & Meier, 2010; Kane, Conway, Miura, & Colflesh, 2007). Specifically, the present task consisted of a series of aurally presented single digit numbers (1–9) via speakers and a series of squares appearing randomly in 9 tile-like positions. The task consisted of 4 blocks, 2 for each *n* condition. Each block consisted of 9 trials (5 control and 4 visual target-trials). After each block, a short break (monitored by the participant, and lasting 5–10 s) was provided to allow some rest. Participants were given the instruction to attend both the visual and the auditory signal for targets and to click as quickly as possible only when a target was perceived.

Visual search. The visual search task consisted of 2 practice blocks of 8 trials each, for the feature and conjunction conditions (Trick & Enns, 1998), respectively. The test phase of the feature search condition constituted by 3 blocks (12, 12, and 8 trials each), with total 32 trials, 8 for each distractor condition (1, 5, 15, and 30 distractors), 4 of each for each target condition (target was either present or absent). In the simple condition, the target was a blue or a pink circle (~0.7 cm in diameter) presented in a shape of rectangular blue and pink shapes (~1 cm wide) arranged horizontally and vertically, representatively. The conjunction condition differed only in the target, which was a vertical rectangular blue shape and horizontal pink shape presented amongst the same pattern of rectangular blue and pink distractors (~1 cm wide) arranged horizontally and vertically, as in the feature search.

Vigilance. The vigilance task was a simple reaction time (RT) task, in which the participants were instructed to press a button as quickly as possible when a certain stimulus would appear. At each trial, a large blue square appeared in the middle of the screen, while a white square appeared either on the top or bottom half of the large square. Participants had to respond by clicking on a touch pad only when the white square appeared on the upper half of the larger square. The test included a practice phase with 5 trials and a test phase with 22 trials, in which the target would appear randomly in 6 trials.

Results

All analyses described above were conducted with the SPSS statistical package.

Bisection Task

In the bisection task the proportion of long responses was computed for all durations, for each participant and age group, and also for the conditions of stimulus types. Then, the psychometric function was fitted, and from this function, *bisection point* (*BP*), *just-noticeable difference* (*JND*) and *Weber ratio* (*WR*) derived. The *BP* is the point of subjective simultaneity (*PSE*), corresponding to the duration at which the participant perceives a particular duration to be short as often as long (proportion of “long” responses, *p* (long) =0.50). The *JND* reflects the steepness of the psychometric function, and a measure of the difference threshold or in the case of the present bisection tasks, the sensitivity with which a participant can discriminate between the intervals in a given task; the steeper the psychometric function, the lower the value of *JND*, which reveals higher sensitivity in interval length discrimination. Lastly, the *WR* is the ratio of *JND* divided by the *BP*; this makes the *WR* a standardized measure of temporal discrimination, and can help in direct comparisons of sensitivity across different durations, with increasing *WR* index the sensitivity to time estimation decreases (Allman & Meck, 2012; Zélanti & Droit-Volet, 2011).

JND, *BP*, and *WR* of all participants were evaluated by 2 x 2 x 3 mixed model ANOVA, with modality (audio, visual), stimulus type (black/white for visual and low/high tone for auditory) as within-participant factors and age group (children/young adults/middle-aged adults) as a between-participant factor (*N*=56). Four participants were excluded from this model: 1 from children's group, 1 from young adults' group and 2 from middle-aged group, being outliers, as their values were outside of the presented duration range. *JND* analyses showed no significant differences between age groups, stimulus types or modalities.

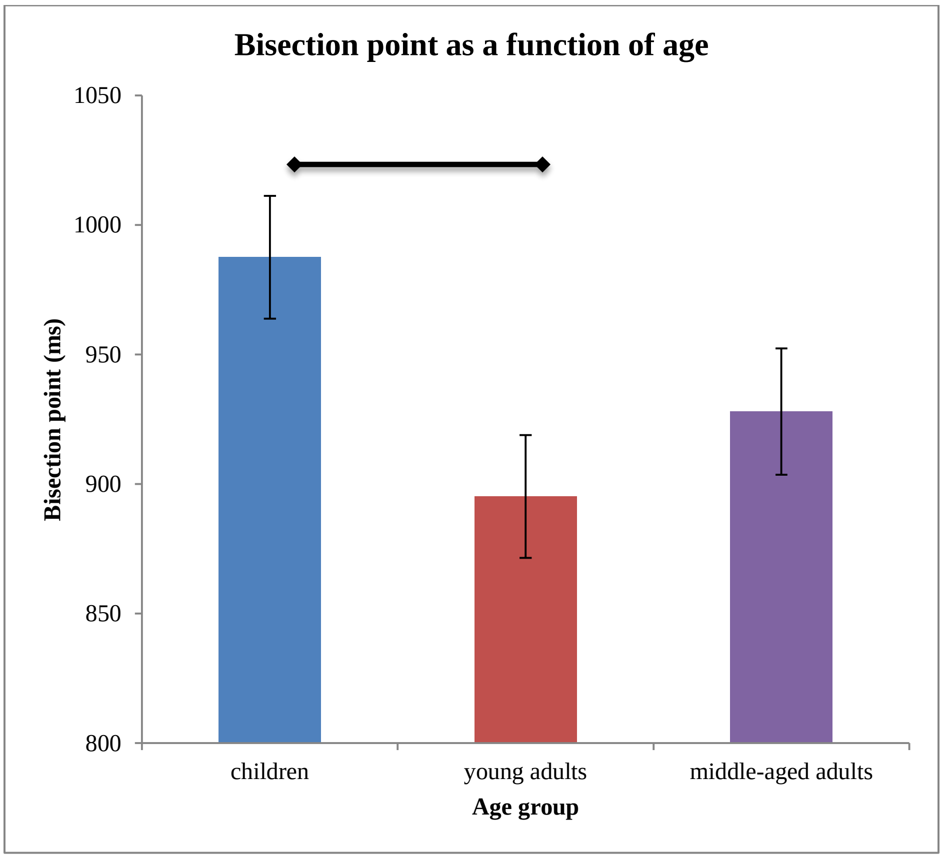

Figure 1. Mean Bisection point with standard errors for each age group in the auditory and visual task.

Analysis for the *BP* uncovered significant main effects of modality, F (1, 53)= 55.66, p<0.001, η_p^2=0.51, with audition having lower mean *BP* (*M*=869.89, *SE*=17.96) than vision (*M*=1003.90, *SE*=14.86). Importantly, a main effect of age was revealed, F (1, 53)= 3.89, p<0.05, η_p^2=0.99, with the between groups comparisons using the Bonferroni correction revealing that children have significantly (p<0.05) higher mean *BP* (*M*=987.50, *SE*=23.72) value than young adults (*M*=895.54, *SE*=23.72) (see Fig. 1). There were no other main effect of stimulus type, F (1, 53)= 0.19, p>0.05, η_p^2=0.004, or interactions between modality and age group, F(2, 53)= 0.09, p>0.05, η_p^2=0.003, between stimulus type and age, F(2, 53)= 0.19, p>0.05, η_p^2=0.007, or between modality, stimulus type and age group, F(2, 53)= 0.30, p>0.05, η_p^2=0.01.

WR analysis also revealed a main effect of modality, F (1, 53)= 17.40, p<0.001, η_p^2=0.25, with vision having lower mean *WR* (*M*=0.54, *SE*=0.02) than audition (*M*=0.71, *SE*=0.05). There was no Stimulus type main effect, F (1, 53)= 0.47, p<0.001, η_p^2=0.001 and no Age main effect (F (2, 53)= 1.18, p>0.05, η_p^2=0.043), Modality × Age interaction, F (2, 53) = 1.91, p>0.05, η_p^2=0.07, the Stimulus type × Age, F (2, 53) = 0.59, p>0.05, η_p^2=0.022, were not significant. Lastly, the Modality × Age × Stimulus type interaction was not significant (F (2, 53) = 0.06, p>0.05, η_p^2=0.002).

Finally, for the proportion of long responses analyses there were no main effects or interactions. However, as we detected a tendency of a rightward shift of the white-circle stimulus condition function of the children's group, we conducted a separate analysis for the white stimulus condition only, analyses despite the absences of statistically significant interactions. A main effect of age was apparent, F (1, 52) = 4.11, p<0.05, η_p^2=0.14, with comparisons showing statistical significant difference (p<0.05) between the children's and young's group as the former had a higher overall mean proportion of long responses (*M*=50.94, *SE*=1.28) than the young group (*M*=45.87, *SE*=1.28) (see Fig. 2).

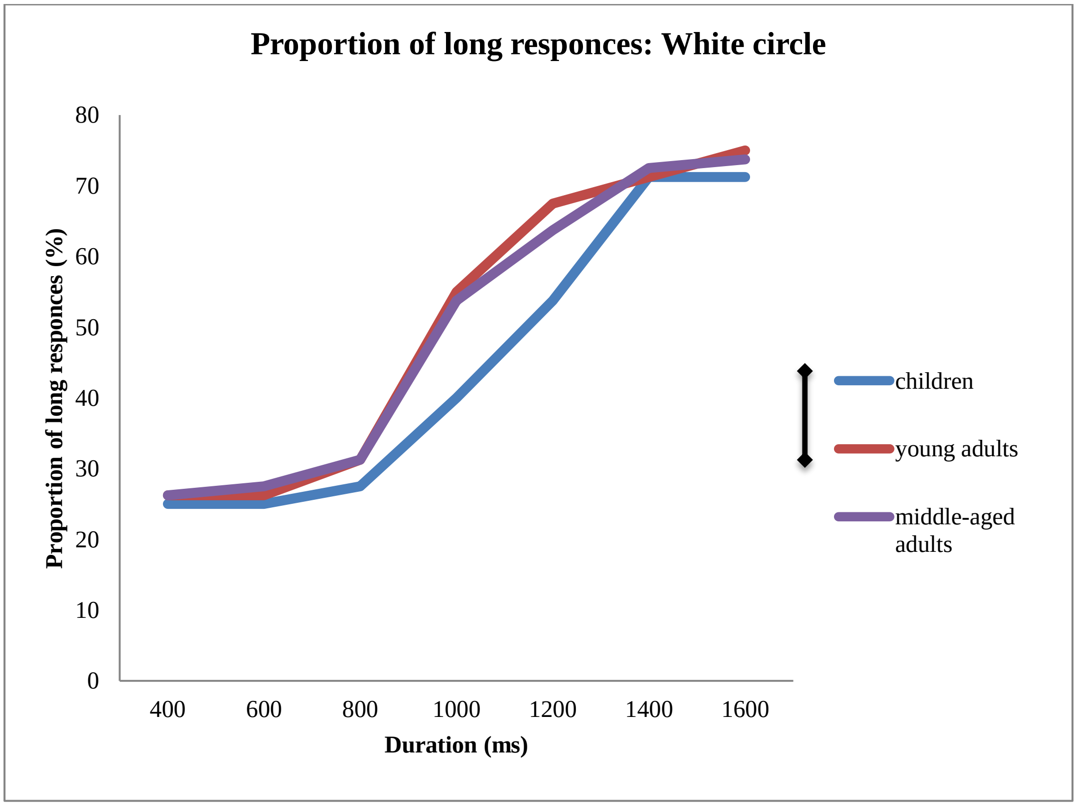

Figure 2. Proportion of long responses for white circle in visual modality. Arrow notes significant difference (p<0.05). Proportion of long responses were significantly different for children and young adults.

Reproduction Tasks

For the analyses of the visual components in the reproduction task, we calculated the *accuracy index* (sometimes referred here as "accuracy"), which is the quotient of the reproduced duration to the actual duration presented, and the *coefficient of variance (CV)*, which is the ratio of the standard deviation to the mean of the reproduced intervals for presented stimuli that lasted the same duration. We put each of this measure in a 2 x 4 x 3 mixed analyses of variance for with duration category (short/long), duration (500/800/1000/1500 for short and 2200/3200/4200/5200 for the long) as within-participant factors and age group (children/young adults/middle-aged adults) as a between-participant factor. For this analysis we had to exclude some outliers based on the *CV*, when this was higher than 1. This lead in the exclusion of 3 individuals in the 13-15 y/o group, 5 individuals in the 20-22yo group, and 1 individual in the 49-51yo group (N=51).

Our analysis model for the *accuracy* measure revealed a main effect of duration category, F (1, 48) = 255.16, p<0.001, η_p^2=0.51. Specifically, the pairwise comparisons, with Bonferroni corrections, showed that short duration category has higher *accuracy index* (M=1.546, SE=0.05) than long category (M=1003.90, SE=14.86), which means overall short durations were overestimated (p<0.001) (see Fig. 3). Interestingly, we observed an anticipated interaction between duration category and age, F (2, 48) = 3.63, p<0.05, η_p^2=0.13. Table 2 shows the mean *accuracy index* for each duration category for the different age groups; within each of the age groups there was a statistical significant overestimation of the short-durations block as compared to the long-durations block (p<0.001) (see Fig. 3). No other main effect or interaction reached significance: Duration, F(3, 144)= 110.23, p>0.05, η_p^2=0.697, Age, F(2, 48)= 2.726, p>0.05, η_p^2=0.102 , Duration × Age, F(6, 144)= 1.52, p>0.05, η_p^2=0.06, Duration Category × Duration × Age, F(3, 144)= 1.199, p>0.05, η_p^2=0.048.

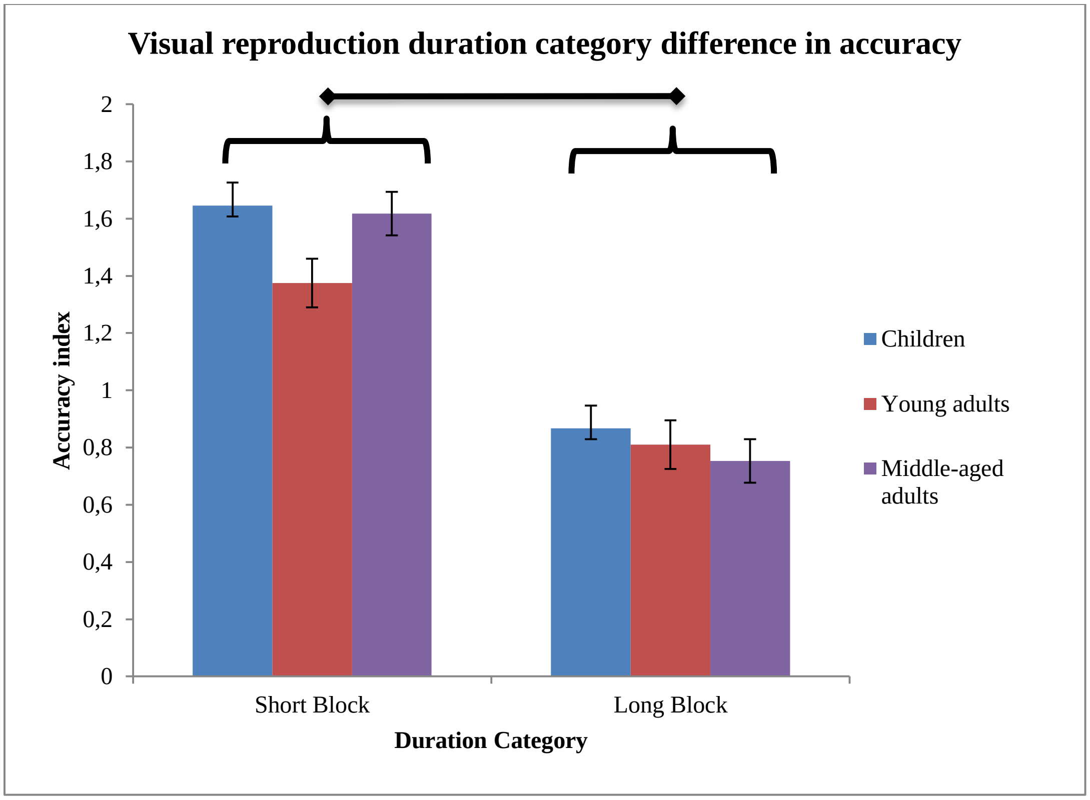

Figure 3. Visual reproduction duration category main effect. Arrow notes significant difference (p<0.05).

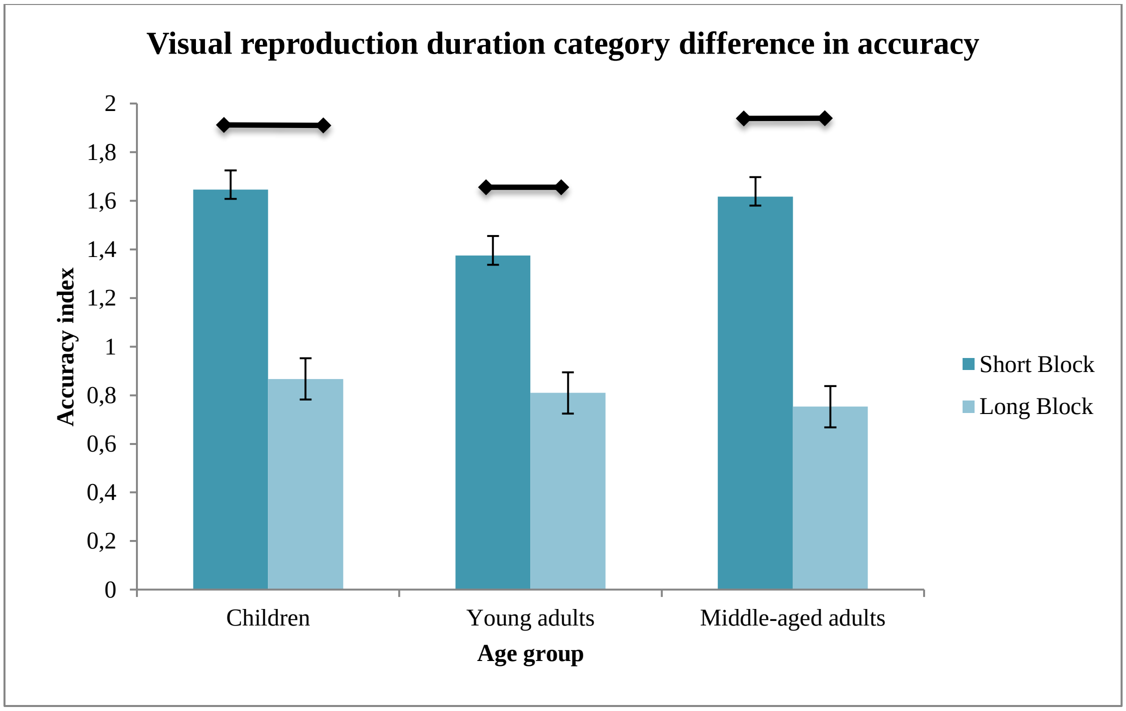

Figure 4. Visual reproduction task's duration category differences within each age group. Arrows note significant difference (p<0.05).

Table 2
Mean accuracy index for short and long duration categories within.

Duration Category	Age group	Mean	Std. Error
Short	children (13-15yo)	1.64	0.08
	young adults (20-22yo)	1.375	0.085
	middle aged adults(49-51yo)	1.618	0.076
Long	children (13-15yo)	0.867	0.038
	young adults(20-22yo)	0.810	0.040
	middle aged adults(49-51yo)	0.753	0.036

Note: within each group the difference between the short and long block was statistically significant (p<0.001).

To further explore the relationship of age and different durations within the duration category blocks, we proceed on conducting separate mixed model in which the duration category condition was collapsed and all 8 durations we used independently in an 8 x 3 mixed model for *accuracy index*. This was done in order to assess the differences of each duration individually and not as a part of a block. This analysis revealed an interesting interaction between duration and age for the measure of *accuracy* (see Fig. 5), F (14, 336)= 2.05, p<0.05 η_p^2=0.08. The Bonferroni corrected multiple comparisons showed a number of comparisons that reached statistical significance for different duration intervals within the age groups. Appendix Table 1 shows the mean estimates for *accuracy* of each presented interval for each group, while in the Appendix Table 4, 5, and 6 the multiple comparisons for the statistically significantly different pairs are listed. In the children's group results, we can understand that generally all groups overestimated the shorter durations of the task. Most importantly in the simple effect of this interaction in the age condition children had higher mean *accuracy* (M=1.72, SE=0.09) than young adults (M=1.35, SE=0.10) in the 800 ms duration (p<0.05), and than the middle aged adults in the 2200 ms duration (M=1.11, SE=0.05) (p<0.05) (see Fig. 5).

As for the analyses of the measure of *CV*, in the original ANOVA model that included the short and long duration category separation, an interaction between duration and age was evident, F(6, 144)= 2.42, p<0.05, η_p^2=0.09. Multiple comparisons with Bonferroni corrections showed that children (M=0.31, SE=0.03) had a higher index than middle-age individuals (M=0.19, SE=0.03) only in the 2^{nd} interval of each duration block (800ms, 2200ms for the short and the long duration block, representatively), thus manifesting higher variability in reproducing the presented duration (p<0.05). No other differences were evident for the factors of Duration Category, F (1, 48= 0.371, p>0.05, η_p^2=0.008, Duration, F (3, 144)= 0.529, p>0.05, η_p^2=0.011, or

Age $F(2, 48) = 1.770$, $p > 0.05$, $\eta_p^2 = 0.069$, and no significant interactions (Duration Category × Age, $F(2, 48) = 0.120$, $p > 0.05$, $\eta_p^2 = 0.084$, Duration Category × Duration × Age, $F(6, 144) = 0.55$, $p > 0.05$, $\eta_p^2 = 0.022$).

When we collapsed the data from the duration categories, using all 8 durations in a separate 8 x 3 mixed ANOVA, to explore the relationship of age and different durations within the duration category blocks as we did for the *accuracy index*, no age related significant main effects or interactions were presented for the *CV*.

In the auditory modality reproduction, a 5 x 2 x 3 x 3 mixed analyses of variance for stimulus type (5 tones and musical intervals), consonance (consonant/dissonant sound) and duration (750/1500/3000), as within-participant factors and age group (children/young adults/middle-aged) as a between-participant factor. Based on the *CV* one participant from the young adults' group was excluded by the analyses model (N=59). No other main effects or interaction relevant with age groups was revealed by this model for the *accuracy index*. However, in the *CV* analysis there was a main effect of age, $F\ (2, 56) = 3.30$, $p < 0.05$, $\eta_p^2 = 0.11$, but no between-groups differences.

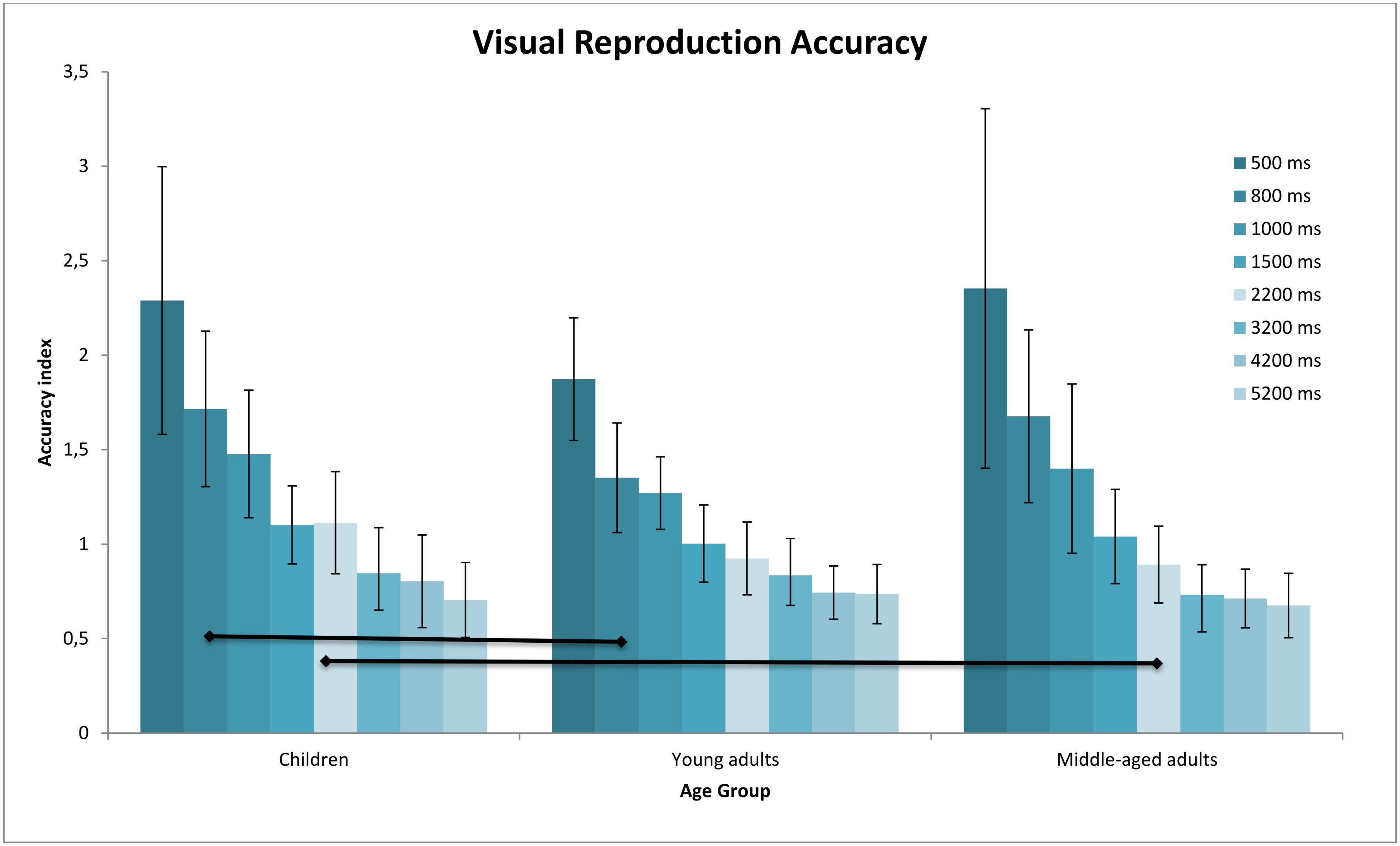

Figure 5. Visual Reproduction task accuracy index by age group and duration. The statistical significant different pairs are listed in the Appendix Table 2, 3 & 4. Arrows note significant difference ($p<0.05$).

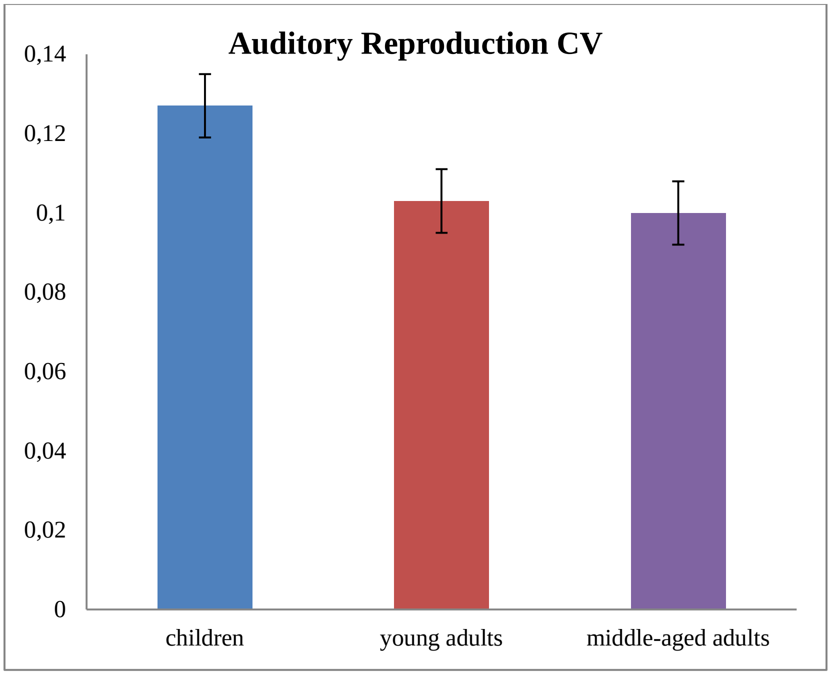

Figure 6. Auditory reproduction task coefficient of variance with Standard Errors. There is a main effect of Age.

Cognitive performance and effects on time estimation

For cognitive performance assessment, from the raw data the average accuracy and the average RT were calculated for each task and each condition. Firstly, we explored correlations and differences between groups in the cognitive tasks in general. In the *n*-back accuracy analyses, there was a main effect of number of *n*-back, F (1, 57) = 38.28, p=0.000, η_p^2=0.40, with participants being significantly better in the 1-back working memory condition (M=0.87, SE=0.2) than the 2-back condition (M=0.76, SE=0.02). There was, also, a main effect *n*-back-type, F (1, 57) = 31.43, p=0.000, η_p^2=0.36, with the control condition (M=0.91, SE=0.1) than the visual condition (M=0.72, SE=0.3). An interaction between *n*-back and *n*-back-type was also evident, F (1, 57) = 23.14, p=0.000, η_p^2=0.29. The comparisons with the Bonferroni corrections showed that in the visual condition of the n-back task the participants had better scores in the 1-back condition (M=0.82, SE=0.03) as compared to the 2-back condition (M=0.63, SE=0.03).

Table 3
Correlation matrix of Bisection task measures and cognitive tests (accuracy and RTs).

	JND			**BP**			**WR**		
Cognitive tasks accuracy	**Overall**	**audio**	**visual**	**Overall**	**audio**	**visual**	**Overall**	**audio**	**visual**
Vigilance	-0.31*	-0.05	-0.42**	0.02	0.05	-0.001	-0.13	-0.02	-0.36**
Feature search	-0.08	-0.13	0.02	-0.09	0.06	-0.24	-0.02	-0.08	0.14
Conjunction search	0.22	0.21	0.10	-0.36**	-0.19	-0.44**	0.35**	0.27*	-0.29*
1-back	-0.20	-0.15	-0.13	-0.24	-0.10	-0.33*	-0.06	-0.12	-0.03
2-back	-0.05	0.14	-0.24	-0.32*	-0.26	-0.29*	0.16	0.17	-0.25
cognitive tasks RT									
vigilance	-0.08	-0.11	0.00	-0.03	-0.01	-0.03	-0.09	-0.10	0.09
Feature search	0.17	0.06	0.20	0.03	0.17	-0.13	0.05	-0.01	0.25
Conjunction search	-0.02	-0.16	0.15	0.19	0.19	0.13	-0.13	-0.17	-0.17
1-back	-0.05	0.02	-0.10	-0.09	-0.10	-0.04	-0.00	0.01	-0.02
2-back	-0.04	0.08	-0.15	-0.27*	-0.17	-0.30*	0.10	0.10	0.01

Notes: ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

Importantly, in the RT analyses of the visual condition (which required a fast response when a target was present), there is an interaction between age and number of *n*-back, F (1, 57) = 3.62, p<0.05, η_p^2=0.11. Exploring this further, the Bonferroni corrected comparisons showed that young adults were faster in the 1-back condition (M=832.12, SE=60.87) than the 1-back (M=995.59, SE=74.73). For the visual search accuracy there was not a significant difference for any condition or group. The only statistically significant result was the main effect of the search type on RTs, F (1, 57) = 3.62, p<0.05, η_p^2=0.11, participants being much faster in the feature search detection of target (*M*=743.72, *SE*=182.55) as compared to the conjunction condition (*M*=2195.74, *SE*=723.20). There was no effect of age. For the vigilance test, we used one-way between groups ANOVAs for the accuracy and the reaction times. They revealed a significant difference of RT parameter F(2)=5.67, p<0.05, as children (*M*=360.35, *SE*=67.25) were significantly faster than young adults (*M*=454.90, *SE*=89.49) (p<0.05), but there was no effect of age on accuracy index for this task.

As the aim of the present study is to explore relationships between age, timing and cognition, we further conducted correlation and regression analyses between the cognitive tasks' score and RTs and the scores in the timing tasks. Therefore, Table 3 presents the correlation matrix among the different timing measures from the bisection task used in this study, and the scores and RTs from the cognitive tasks. As revealed here all the cognitive tasks score are correlated with at least one timing value, while only the 2-back working memory tasks condition RT is correlated with overall *BP* and visual *BP*. To examine cognitive effects and age in timing further, we run regression analyses on the *BP*, with age and the cognitive assessment measures (feature search, conjunction search, vigilance accuracy and RTs, as well as 1-back, 2-back accuracy and visual 1-back, 2-back RTs) being entered in the equation. Our hierarchical regression did not produce any significant results.

Moreover, we, similarly, conducted analyses for the temporal reproduction tasks. Table 5 shows the correlation analyses among timing indexes of the visual reproduction task, age, and cognitive tests (accuracy and RTs). In Table 6 and Table 7, the correlation matrix is presented for the *accuracy* and the *CV* of the auditory reproduction task, representatively, along with the age, and cognitive test scores and RTs. In the visual reproduction task, regression analyses were conducted for each one of the following parameters: overall *accuracy* and *CV*, short and long duration category and 500, 800, 1000, 1500, 2200, 3200, 4200,5200 ms duration condition *accuracy* and *CV*. The factors that served as predictors were again: feature search, conjunction search, vigilance accuracy and RTs, as well as 1-back, 2-back accuracy and visual 1-back, 2-back RTs. Hierarchical regression, firstly, controlling for age and adding the cognitive factors along with age in a second model were run. This produced the significant results seen in Table 4. Age was a significant predictor for "Long duration" 's *accuracy* and *CV*, 2200 ms and 3200 ms durations but it only explained a small amount of the variance, specifically, 9%, 9%. 15% and 13%, representatively. However, age with the cognitive factors could predict the 43% an 49% of the variance for the reproduction response in 800 ms and 2200ms conditions.

Table 4.
Statistically significant Regression models and R^2 for the auditory reproduction task.

Model	**Dependent Variable**	***Sum of Squares***	***df***	***Mean Square***	***F***	***p(Regression)***	***R^2***	***p (R^2)***
	Accuracy							
1	Long durations	0.12	1.00	0.12	4.94	0.03	0.09	0.03
2	800 ms	3.79	13.00	0.29	2.11	0.04	0.43	0.03
1	2200 ms	0.43	1.00	0.43	8.41	0.01	0.15	0.01
	CV							
1	Long durations	0.09	1.00	0.09	4.54	0.04	0.09	0.04
2	500 ms	0.72	13.00	0.06	2.73	0.01	0.49	0.02
1	3200 ms	0.28	1.00	0.28	7.02	0.01	0.13	0.011

Note: Model 1 corresponds to age as a predictor, Model 2 corresponds to predictors: age, feature search, conjunction search, vigilance accuracy and RTs, as well as 1-back, 2-back accuracy and visual and control 1-back, 2-back accuracy and RTs.

Table 5
Correlation matrix among timing indexes of the visual reproduction task, age, and cognitive tests (accuracy and RTs).

	Accuracy			**CV**		
	All durations	**Short durations**	**Long durations**	**All durations**	**Short durations**	**Long durations**
Age	-0.14	-0.02	-0.30*	-0.22	-0.02	-0.29*
Accuracy						
Vigilance	-0.10	-0.15	0.05	-0.14	-0.08	-0.14
Feature visual search	-0.07	-0.09	0.01	-0.11	-0.15	-0.05
Conjunction visual search	-0.14	-0.22	0.12	-0.10	-0.06	-0.11
1-back	-0.11	-0.20	0.16	-0.23	-0.21	-0.18
2-back	-0.12	-0.19	0.10	-0.17	-0.21	-0.10
1-back (control)	-0.17	-0.21	0.01	0.01	-0.02	0.02
1-back (visual)	-0.06	-0.15	0.17	-0.26	-0.23	-0.21
2-back (control)	-0.023	-0.04	0.07	-0.02	0.11	-0.09
2-back (visual)	-0.11	-0.17	0.09	-0.15	-0.24	-0.06
RT						
Vigilance	-0.01	0.04	-0.10	-0.17	-0.14	-0.15
Feature visual search	0.32*	0.34*	0.08	-0.02	0.14	-0.11
Conjunction visual search	0.22	0.18	0.17	0.06	0.13	-0.00
1-back (visual)	0.17	0.27	-0.15	0.07	0.17	-0.01
2-back (visual)	-0.11	-0.11	-0.04	-0.20	-0.07	-0.24

* Notes:* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 6
Correlations matrix for the auditory reproduction accuracy, age and cognitive tests (accuracy and RTs).

	Accuracy						Accuracy (Consonant)			Accuracy (dissonant)		
	Overall	750 ms	1500 ms	3000 ms	Consonant	dissonant	750 ms	1500 ms	3000 ms	750 ms	1500 ms	3000 ms
age	0.00	-0.01	-0.02	0.06	0.03	-0.03	0.02	0.00	0.07	-0.04	-0.05	0.05
Accuracy												
vigilance	0.04	0.04	0.05	0.01	0.05	0.03	0.02	0.06	0.03	0.05	0.03	-0.02
feature	0.33*	0.04	0.67**	0.15	0.49**	0.13	0.05	0.84**	0.11	0.04	0.18	0.19
conjunction	0.23	0.00	0.40**	0.26*	0.31*	0.13	0.00	0.46**	0.27*	0.00	0.19	0.25
1-back	0.09	-0.06	0.14	0.24	0.10	0.07	-0.05	0.13	0.24	-0.06	0.12	0.23
2-back	0.11	0.00	0.19	0.16	0.13	0.09	0.00	0.17	0.16	0.00	0.16	0.15
RT												
vigilance	0.07	0.15	-0.03	0.02	0.07	0.05	0.20	-0.05	0.04	0.09	0.01	0.01
feature	0.17	0.33*	0.00	0.01	0.14	0.18	0.31*	-0.02	0.04	0.33*	0.03	-0.02
conjunction	-0.04	-0.01	-0.06	-0.03	-0.04	-0.03	-0.03	-0.06	0.02	0.01	-0.05	-0.07
1-back (visual)	-0.01	-0.03	0.01	0.03	0.01	-0.02	0.01	0.00	0.03	-0.06	0.02	0.03
2-back (visual)	-0.02	0.03	-0.06	-0.03	-0.02	-0.01	0.01	-0.04	-0.03	0.05	-0.09	-0.04

Notes:* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 7
Correlations matrix for the auditory reproduction CV, age and cognitive tests (accuracy and RTs).

	CV						CV (Consonant)			CV (dissonant)		
	Overall	750 ms	1500ms	3000 ms	Consonant	dissonant	750 ms	1500 ms	3000 ms	750 ms	1500 ms	3000 ms
age	-0.23	-0.12	-.299*	-0.16	-0.15	-0.278*	-0.06	-0.21	-0.09	-0.14	-.317*	-0.19
Accuracy												
vigilance	0.07	0.12	-0.03	0.06	0.11	0.03	0.15	0.05	0.05	0.07	-0.08	0.06
feature	-0.02	-0.13	0.15	-0.04	-0.01	-0.03	-0.12	0.16	-0.04	-0.12	0.11	-0.03
conjunction	-0.05	-0.18	0.11	-0.01	-0.01	-0.08	-0.18	0.15	0.05	-0.18	0.09	-0.06
1-back	-0.26*	-0.22	-0.21	-0.20	-0.20	-0.289*	-0.20	-0.10	-0.18	-0.21	-0.26	-0.17
2-back	-0.04	0.09	-0.07	-0.16	-0.03	-0.05	-0.01	0.01	-0.07	0.13	-0.10	-0.20
RT												
vigilance	-0.10	-0.08	-0.17	0.02	-0.09	-0.09	-0.14	-0.05	-0.01	-0.02	-0.25	0.04
feature	0.19	0.14	0.05	0.284*	0.16	0.21	0.14	0.07	0.16	0.14	0.00	0.33*
conjunction	-0.14	-0.19	-0.16	0.04	-0.19	-0.08	-0.19	-0.19	-0.05	-0.15	-0.10	0.12
1-back (visual)	-0.02	0.02	0.03	-0.12	-0.06	0.01	-0.09	0.05	-0.09	0.10	0.01	-0.11
2-back (visual)	0.04	0.23	-0.16	-0.02	0.04	0.04	0.08	-0.01	0.02	0.29*	-0.25	-0.05

Notes:* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

We ran regression analyses on the auditory temporal reproduction task parameters, *accuracy* and *CV*, with age and the cognitive assessment measures (feature search, conjunction search, vigilance accuracy and RTs, as well as 1-back, 2-back accuracy and visual and control 1-back, 2-back accuracy and RTs) being entered in the equation. The regression revealed that age along with all the cognitive scores were statistically significant predictors of the 45.5% of the variance, R^2= 0.45, p< 0.05 for the overall accuracy index increment (*F*(13)=2.89, *p*<0.05). In this model, there were particularly 2 factors that had significant contribution in the model: feature search accuracy, β=-0.58, *t* (37) = 4.35, *p*=0.000, conjunction search RT, β=-0.47, *t* (37) = -2.18, *p* < 0.05. Similarly, for the 750 ms and the 3000 ms durations accuracy our model could predict 41.8% of the variance, R^2= 0.42, p< 0.05 for the overall accuracy index increment (*F* (13) = 2.48, *p*<0.05), and 58.4%% of the variance, R^2= 0.58, p< 0.05 for the overall accuracy index increment (*F* (13) = 4.85, p=0.000) (Table 8). Here the most important contributors were feature search accuracy (750 ms, β =0.50, *t* (37) = 3.65, *p*<0.05, 3000 ms, β =-0.68, *t* (37) = 5.87, *p*=0.000), conjunction search RT, (750 mς, β =0.40, *t* (37) = 2.61, *p* < 0.05, 3000 ms, β =-0.27, *t* (37) = -2.20, *p*<0.05). Stimulus type conditions accuracy was also predicted by adding age and the cognitive tasks scores to the model, which was also the case for the regression for the 750 ms duration *CV* (see Table 8 for *F*, $R^2$and *p* values). Lastly, only age was a predictor for 1500 ms *CV*, which is the intermediate duration of the auditory reproduction task, but it could only account for the 9% of the variance (see Table 8).

Table 8.
Statistically significant Regression models and R^2 for the auditory reproduction task.

Model	Dependent Variable	*Sum of Squares*	*df*	*Mean Square*	*F*	*P (Regression)*	R^2	$p (R^2)$
	Accuracy							
2	Overall	3.869	13	0.298	2.893	0.004	0.455	0.003
2	750 ms	7.66	13	0.589	2.483	0.012	0.418	0.008
2	3000 ms	3.054	13	0.235	4.851	0	0.584	0.00
2	Consonant	4.299	13	0.331	2.611	0.009	0.43	0.006
2	Dissonant	3.672	13	0.282	2.785	0.005	0.45	0.004
	CV							
2	750 ms	0.092	13	0.007	2.047	0.038	0.372	0.033
1	1500 ms	0.013	1	0.013	5.614	0.021	0.09	0.021

Note: Model 1 corresponds to age as a predictor, Model 2 corresponds to predictors: age, feature search, conjunction search, vigilance accuracy and RTs, as well as 1-back, 2-back accuracy and visual and control 1-back, 2-back accuracy and RTs

Discussion

The current study included the examination of children, young, and middle adults in temporal reproduction and bisection tasks in order to detect time-estimation differences between the groups. Importantly we administered cognitive tests to examine whether differences between the groups are due to specific age-related alterations of the basic cognitive capacities such as memory and attention, especially for the 13-15 y/o group where we hypothesized that they would not have reached an adult-like performance. Our investigation resulted in significant age-related difference in the timing parameters although mostly in the children and not in the middle aged group, as well as, consequent correlations with the cognitive tests' parameters.

In detail, children underestimated the presented intervals compared to YA, as they had higher overall *BP* and a rightward shift in proportion of long responses in one of the visual conditions. This is in line with previous results stating, firstly, that children are able to estimate intervals similarly with healthy humans but have slower pacemaker clock. We, also, observed increased proportion of long responses with increasing physical duration as in previous studies (e.g., Brannon, Suanda, & Libertus, 2007; Provasi, Rattat, & Droit-Volet, 2011). For response variance we found lower sensitivity in children than the other two groups, as the analysis revealed higher variance for children as compared to 49-51 y/o group in some interval from the visual reproduction task, as well as overestimation for some duration as compared to YA and middle group. These differences extend findings by Droit-Volet's and colleagues work on the field of time estimation in childhood (e.g., Droit-Volet & Hallez, 2018; Droit-Volet & Zélanti, 2012; Rattat & Droit-Volet, 2001; Zélanti & Droit-Volet, 2011), who have found ability to estimate time but with overestimation and lower sensitivity that is generally improved as they grow older (studies include children from 3 to 11 years old).

Variance seemed to be influenced by age in the auditory reproduction task, too. Likewise, there have been reports of that children have higher variability in their estimation of time and they also reproduce intervals with higher variability than older groups (Block, Zakay, & Hancock, 1999). These reproduction findings generally "agree" with the bisection studies predictions of lower temporal sensitivity and slower internal clock in children. Furthermore, it has been demonstrated for ages 3 to 11 y/o that temporal sensitivity is low, as children have higher WR and flatter function of proportion of long responses (Droit-Volet, 2017; Clément & Droit-Volet, 2006; Droit-Volet et al., 2006). The absence of such a result in the bisection task and the evidence of higher variability only in the temporal reproduction are not contradictory to the above studies. This is because as mentioned before the field of time estimation in childhood have examined mostly individuals from infancy to 11 y/o and our study included the range of 13 to 15. Children at this age seem to be getting better in interval estimation for reproduction, while in bisection it has been reported that variability is getting lower through childhood, suggesting that age related improvements account for the lack of differences in discrimination variability in the present study.

On the other hand, this study failed to derive any difference between the MA group and the YA group. This absence of contrasting data between YA and middle aged ones shows that it is necessary to examine age related changes closely, in order to detect seminal points of timing processing deteriorations. For the first time, we presented a more spherical temporal “profile” of individuals in late childhood and in the beginning of middle age; in addition, we introduced small age-range of YA and MA individuals – meaning including participants with very similar characteristics, age-wise –was tested and compared with that of late childhood group. Most children studies already have small age ranges in order to create groups, but it seems to be important to not only control the adults group ranges strictly but also include more than one adult group when comparing with children, adolescents or elderly. It is, also, important to mention that in a study by Block et al. (1999), age-related differences were less “pronounced” in the bisection task and all groups produced *BP* close to the arithmetic mean of the paradigm’s durations. In our bisection paradigm, we partially confirmed this finding as we could not detect any difference between middle-aged adults and the other adult group.

Another significant result derived through the regression modeling of timing parameters with the cognitive scores and RTs. It has already been suggested that numerous cognitive factors may contribute to developmental timing processing changes, such as attention and inhibition (Block et al., 1998, 1999). It is important to note here that because of the absence of age-related significant results in all the timing parameters, we controlled for age in regression analyses, doing hierarchical models. Thus, even when age was not a significant factor but a confounding one for our results, adding the cognitive assessment factors into the prediction model could account for statistically significant amount of variance in our dependent variable (after controlling for age). Our regression modeling showed that cognitive factors – that is, feature search, conjunction search, *n*-back accuracy and vigilance accuracy as well as RTs – were significant predictors in overall temporal reproduction accuracy index in the auditory modality, as well as consonant and dissonant sound accuracy. Moreover, in the auditory reproduction paradigm, we found that for the intermediate durations, the only major predictor was age, while in the shortest and the longest duration *accuracy* and *CV* values, the variance was explained at significant level by our other predictors and not solely age, meaning cognitive factors have a significant role in the results within a block of a certain time scale. More importantly, cognitive factors predicted a large amount of variance for the shortest and the longest of the setups duration accuracy and the shortest duration variance (i.e.750 ms *CV*). Similarly, in the temporal reproduction for the visual modality, the cognitive factors predicted almost half of the variance of the 500 ms *CV* and 800ms accuracy, which represented this task's shortest interval. Again, this is in line with a previous report (Zelanti & Droit-Volet, 2011): the bisection paradigm used in the aforementioned study, completed by children and young adult groups, revealed that the paradigms intermediate durations could only be explained by age but their shortest and longest durations explained when adding the scores from neuropsychological tests to their regression model (Zelanti & Droit-Volet, 2011).

The present study, additionally, supports high correlations of *BP*, *WR*, *JND*, as well as visual and auditory reproduction accuracy index and *CV* with the cognitive factors. Specifically, vigilance was correlated with *JND* and *WR*, and working memory accuracy with *BP* and auditory reproduction *CV*. Conjunction and feature search indexes seemed to be associated with most of the temporal measures *WR*, *BP*, auditory reproduction *accuracy* and *CV*, and visual reproduction accuracy. Our findings, thus, support the idea that the attentional capacities are essential in the observed variability of individual temporal responses. A number of studies have firmly establish that the processing of time is attentionally demanding as it requires sustained attention; participants must focus and maintain attention across the continuous passage of time (Coull, 2004; Coull, Vidal, Nazarian, & Macar, 2004; Lewis & Miall, 2009). It have been suggested that young children's lower sensitivity to time is mainly due to limited attention or working memory capacities (Delgado & Droit-Volet, 2007; Droit-Volet, Wearden, & Delgado-Yonger, 2007b; McCormack, Wearden, Smith, & Brown, 2005). Droit-Volet (2003) has demonstrated that attention on the onset of the stimulus presented in timing task is more variable in young children than that of their older counterparts. We also suggest here that the overall similarity of 13-15 y/o responses to those of the adult groups may be due to maturation of response inhibition and processing speed, which have been shown to reach adult-performance levels between the ages of 14 and 15 years old (Huizinga, Dolan, & van der Molen, 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

Summarizing, in this thesis we used bisection and reproduction tasks with different durations and age-groups that are rarely used or compared with each other. It was revealed that individuals in late childhood were worse in estimating time durations but we observed no impairment in duration estimation for middle-aged individuals in the range of 49-51 y/o. In addition, the regression analyses revealed that attention and working memory capacities explained those age-group differences in time discrimination. Importantly, we revealed temporal differences in the way participant judged duration of stimuli with different color. Further work must be done in order to decipher the particular ways timing processing is reaching adult-level maturation performance, as well as the point in life-time that duration estimation starts deteriorating. We suggest that, direct comparisons of multiple children and adult group with the same set of paradigms (e.g., discrimination, production, reproduction) should be examined, with the smaller age-ranges and extensive cognitive comparisons between groups.

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Appendix

Appendix Table 1
Mean accuracy index for each duration and age group for the visual reproduction group.

Duration (ms)	**Age group**	Mean	Std. Error
500	Children (13-15y/o)	2.289	0.177
	Young adults(20-22y/o)	1.873	0.189
	Middle-aged adults(49-51y/o)	2.353	0.168
800	Children (13-15y/o)	1.715	0.096
	Young adults(20-22y/o)	1.351	0.103
	Middle-aged adults(49-51y/o)	1.677	0.091
1000	Children (13-15y/o)	1.477	0.085
	Young adults(20-22y/o)	1.270	0.090
	Middle-aged adults(49-51y/o)	1.399	0.080
1500	Children (13-15y/o)	1.101	0.054
	Young adults(20-22y/o)	1.002	0.057
	Middle-aged adults(49-51y/o)	1.040	0.051
2200	Children (13-15y/o)	1.112	0.054
	Young adults(20-22y/o)	0.924	0.058
	Middle-aged adults(49-51y/o)	0.891	0.051
3200	Children (13-15y/o)	0.845	0.044
	Young adults(20-22y/o)	0.835	0.047
	Middle-aged adults(49-51y/o)	0.731	0.042
4200	Children (13-15y/o)	0.803	0.045
	Young adults(20-22y/o)	0.743	0.048
	Middle-aged adults(49-51y/o)	0.712	0.042
5200	Children (13-15y/o)	0.704	0.042
	Young adults(20-22y/o)	0.735	0.045
	Middle-aged adults(49-51y/o)	0.675	0.040

Appendix Table 2
Mean accuracy index for each duration in the children's group for the visual reproduction task.

Age group	Duration (ms)	Comparison duration (ms)	Mean Difference between duration pair	Std. Error	Sig.
children (13-15y/o)	500	800	0.57	0.164	0.03
		1000	0.81	0.162	0.00
		1500	10.19	0.182	0.00
		2200	10.18	0.181	0.00
		3200	10.44	0.180	0.00
		4200	10.49	0.191	0.00
		5200	10.59	0.179	0.00
	800	1000	0.24	0.062	0.01
		1500	0.61	0.084	0.00
		2200	0.60	0.091	0.00
		3200	0.87	0.099	0.00
		4200	0.91	0.106	0.00
		5200	10.01	0.09	0.00
	1000	1500	0.38	0.068	0.00
		2200	0.36	0.079	0.00
		3200	0.63	0.083	0.00
		4200	0.67	0.092	0.00
		5200	0.77	0.085	0.00
		500	-10.19	0.182	0.00
		800	-0.61	0.084	0.00
		1000	-0.38	0.068	0.00
	1500	3200	0.26	0.055	0.00
		4200	0.30	0.054	0.00
		5200	0.40	0.052	0.00
	2200	3200	0.27	0.044	0.00
		4200	0.31	0.051	0.00
		5200	0.41	0.057	0.00
	3200	5200	0.14	0.037	0.01

Note: Reported all the significant results only. Adjustment for multiple comparisons: Bonferroni.

Appendix Table 3
Mean estimates of accuracy for each duration in the young adults'group

Age group	Duration (ms)	Comparison duration (ms)	Mean Difference between duration pair	Std. Error	Sig.
young adults (20-22y/o)	500	1000	0.60	0.173	0.03
		1500	0.87	0.194	0.00
		2200	0.95	0.195	0.00
		3200	10.04	0.192	0.00
		4200	10.13	0.203	0.00
		5200	10.14	0.190	0.00
	800	1500	0.35	0.090	0.01
		2200	0.43	0.097	0.00
		3200	0.52	0.105	0.00
		4200	0.61	0.113	0.00
		5200	0.62	0.104	0.00
	1000	1500	0.27	0.073	0.02
		2200	0.35	0.084	0.00
		3200	0.44	0.088	0.00
		4200	0.53	0.098	0.00
		5200	0.54	0.091	0.00
	1500	3200	0.17	0.058	0.18
		4200	0.26	0.058	0.00
		5200	0.27	0.056	0.00
	2200	4200	0.18	0.054	0.05

Note: Reported all the significant results only. Adjustment for multiple comparisons: Bonferroni.

Appendix Table 4
Mean estimates of accuracy for each duration in the middle-aged adults

Age group	Duration (ms)	Comparison duration (ms)	Mean Difference between duration pair	Std. Error	Sig.
Middle-aged adults (49-51y/o)	500	800	0.68	0.155	0.00
		1000	0.95	0.154	0.00
		1500	10.31	0.172	0.00
		2200	10.46	0.174	0.00
		3200	10.62	0.171	0.00
		4200	10.61	0.181	0.00
		5200	10.68	0.169	0.00
	800	1000	0.28	0.058	0.00
		1500	0.64	0.080	0.00
		2200	0.79	0.086	0.00
		3200	0.95	0.093	0.00
		4200	0.97	0.100	0.00
		5200	10.00	0.092	0.00
	1000	1500	0.36	0.065	0.00
		2200	0.51	0.075	0.00
		3200	0.67	0.078	0.00
		4200	0.69	0.087	0.00
		5200	0.73	0.081	0.00
	1500	3200	0.31	0.052	0.00
		4200	0.33	0.051	0.00
		5200	0.37	0.049	0.00
	2200	3200	0.16	0.042	0.01
		4200	0.18	0.048	0.02
		5200	0.22	0.054	0.01

Note: Reported all the significant results only. Adjustment for multiple comparisons: Bonferroni.