Title

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Abstract

Most previous studies on time perception have examined temporal order and distance judgments in isolation using controlled stimuli. However, in real life, these two elementary temporal experiences are related. Here, we examine the effects of age and event structure on temporal estimation and introduce a novel timeline estimation paradigm comprising temporal order and distance judgments with naturalistic stimuli. In two experiments, we asked participants to view a three-minute-long video clip and mark the temporal order and distance of a specific scene of the video on a horizontal timeline. In the first experiment, we conducted the timeline estimation task with three different age groups – 6-8-year-olds, 9-11-year-olds and adults – and found age-related differences in the participants' accuracy and variability of temporal estimation. The nonlinearity between their estimates and stimulus distance decreased as their ages increased. In Experiment 2, we tested the effect of event structure on participants' timeline estimation and observed that more complicated video resulted in more distorted temporal estimation. In sum, the current study corroborated the timeline estimation task to be a valuable tool for assessing temporal judgments across development.

Keywords: temporal order memory; duration judgment; time estimation; temporal concept development

Previous studies on time perception have primarily examined temporal distance (duration) perception, temporal order judgments, and episodic/autobiographical memory (Allman, Teki & Griffith, 2014; Grondin, 2010). Specifically, the former two areas have been investigated extensively using different experimental paradigms in isolation. Regarding temporal distance perception, prior research has used interval reproduction, comparison, and temporal bisection tasks with simple visual shapes or acoustic tones to examine subject's temporal distance perception over milliseconds and seconds.

However, the experimental procedure of classical temporal distance perception has significant limitations for covering a broad range of intervals. For example, since the temporal bisection task, one of the most widely used tasks in the temporal distance perception literature, requires registering the length of the referent stimulus in the short-term memory, it cannot be extended beyond several seconds without secondary strategies such as counting and tapping. Furthermore, pure interval timing beyond several seconds would be an unnatural human timing process because in daily life, temporal distance perception over several seconds would be accompanied by other cognitive processes, such as event perception and memory. Lastly, methodological demands encourage the use of conscious time-keeping strategies (prospective timing), but these strategies are not commonly used in everyday life. Therefore, recent studies have argued that some previous findings in temporal distance perception are incompatible with ordinary interval timing experiences (Boltz, 2005; Droit-Volet, Trahanias, & Maniadakis, 2017).

On the other hand, temporal order memory studies have relied on retrospective timing; thus, the participants did not know that they would be asked to make a time judgment until after an event had taken place. Therefore, this paradigm assesses the temporal relation remembered between events, which is ecologically more valid. Nonetheless, temporal order memory studies have investigated controlled stimuli, similar to the temporal distance perception studies. Although such stimuli can provide rigorous experimental control, it is not always clear whether the results of their use can be generalized to everyday events. Specifically, given the importance of people's attention to time perception (Boltz, 1999; Brown, 2008; Grondin, 2010), time perception with realistic stimuli may be substantially different from that with the highly-controlled stimuli.

Therefore, it has been argued that the time estimation literature should have involved tasks with more ecological validity (Boltz, 2005; Brown & West, 1990; Carell, 2011; DuBrow & Davachi, 2016). However, the attempts at conducting empirical research with realistic stimuli (Bisson, Tobin & Grondin, 2012; Tobin, Bisson & Grondin, 2010, Droit-Volet, Trahanias, & Maniadaks, 2017, Nielson et al., 2015) still have not produced conclusive answers about similarities and dissimilarities between naturalistic and highly controlled time perception. In addition, they have not attempted to investigate temporal distance and order experiences simultaneously as in real life.

Given these limitations, we developed a novel temporal judgment task (a) involving both temporal distance and order perception (b) using more natural stimuli (c) ranging from seconds to minutes (d) under both retrospective and prospective timing (e) without relying on temporal word knowledge to investigate the effects of age and event structure on temporal estimation. In this task, we asked

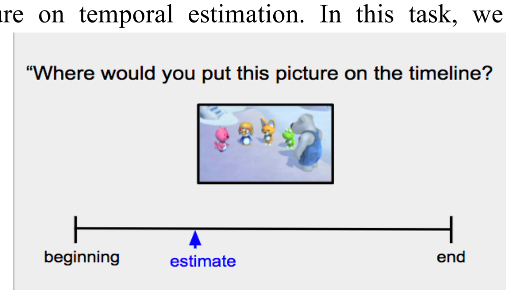

Figure 1. An example of a timeline task

participants to study a three-minute-long video clip excerpted from commercial movies; then, we presented participants with a still picture from the video clip and a concrete horizontal line, referred to as a 'timeline,' and asked them to identify the temporal position of the still picture on the timeline.

In Experiment 1, we investigated developmental changes in different age groups – 6-8-year-olds, 9-11-year-olds and adults – and these groups' temporal judgment of minute-range intervals with the mean estimates and variation of judgments. In Experiment 2, we investigated whether the event structure of the stimuli and timing paradigms (prospective/retrospective) affected the adults' timeline estimation performance.

Experiment 1

In Experiment 1, we present a novel "timeline estimation" task, which (a) does not rely on participants' temporal word knowledge, (b) uses a realistic event as a stimulus, and (c) involves both temporal distance and order judgments. We compared the mean estimates and variations of temporal judgment across different age groups to investigate the developmental changes for each judgment.

Method

Participants. Experiment 1 included three age groups: 6-8-year-old children, 9-11-year-old children and adults. A total of 105 children were recruited from schools in Columbus, Ohio. Parents of the children provided written consent. The adult participants were 34 undergraduate students who participated in exchange for a course credit at the Ohio State University.

Materials and Procedure. Participants carried out the timeline estimation task consisting of initial learning, math problem solving, and testing phases. In the learning phase, we presented the participants with a three-minute-long video clip. To control for the confounding effect of narrative on temporal judgment, we removed the sound of the stimuli. We instructed the participants to pay attention to and remember the contents of the video. After the initial learning phase, we asked the participants to solve five math problems to control for the recency effect of short-term memory. We modulated the difficulty of the math problems according to the participant's age. We created 30 still pictures from every six seconds of the video clip for all participants and randomly chose 40 of these still pictures for each participant to observe. In the testing phase, we gave the participants a timeline estimation task in which we presented a timeline with the 40 still pictures; one picture was shown per trial. In each trial, we instructed the participants to indicate approximately when the still picture appeared while they were watching the video by marking the corresponding place on the timeline using a mouse click (see Figure 1). We did not provide feedback on their performance.

Analyses. We evaluated the participants' mean estimates, percent absolute errors (PAEs), coefficients of variation (CVs), and nonlinearity scores. One method for obtaining an overall sense of the participants' estimate efficiency is the PAE, which was calculated as follows (Siegler & Booth, 2004):

$$\text{PAE} = \frac{|Response - Stimulus|}{Scale\ of\ estimates}$$

Another way of assessing the participants' efficiency is by using the CV which was calculated as the standard deviation of the estimates divided by the mean estimate. According to one of the most widely accepted 'scalar property' principles in the field of interval timing (Gibbon, 1977), the CV should remain constant across a range of intervals if temporal perception follows Weber's law as other sensory dimension perceptions do. This property is considered as evidence of any single mechanism by which given intervals are timed. Thus, we calculated the CV across subjects and tested whether it was constant across the length of a timeline and whether there were any developmental differences according to the CV change.

Lastly, in line with the procedure of Cicchini et al. (2014) in a number-line study, we regressed the participants' estimates against the target distance using a combined log-linear regression model:

$$R = a\left\{(1-\lambda)T + \lambda * \frac{T_{max}}{\ln(T_{max})} * \ln(T)\right\}$$

where R denotes the response to the given target distance T, a is a scaling factor, and T_{max} is the distance at the right end of the timeline (180 in the current study). The degree of nonlinearity is denoted by λ. If λ equals 0, the relation between the estimates and target distances is perfectly linear, whereas if λ is 1, the relation is perfectly logarithmic.

The linear relationship indicates that the participants perceived the correct temporal order of the given stimuli, as well as the distance between them, as constant across the time range. On the other hand, the nonlinear (logarithmic) relation indicates that the participants overestimated the distance of the initial events and underestimated the distance of the

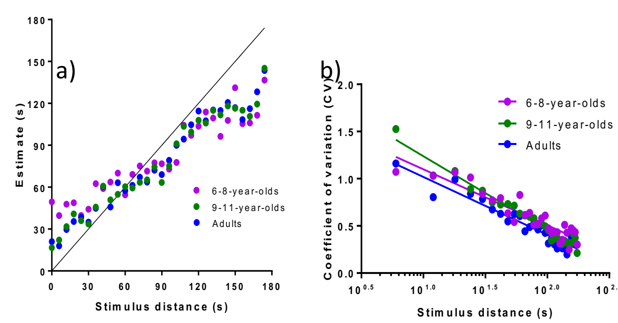

Figure 2. a) Participants' estimates along the target duration, b) logarithmic decrease in CV with increase in target duration.

events near the end of the range. In addition, previous studies using the number line estimation task, which has a similar task structure to the timeline task, reported a logarithmic to linear shift across development (Kim & Opfer, 2015; Siegler & Booth, 2004; Siegler & Opfer, 2003). We also aimed to examine whether there was a similar shift in temporal estimation.

Results and Discussion

Mean Estimates and CVs. First, as Figure 2a shows, the mean estimate increased as the target interval increased across the three different age groups. Although the estimates and target intervals were not perfectly linear mapped, the adults and 9-11-year-old children showed a relatively more linear pattern than the 6-8-year-old children, $F(2, 136) = 6.65$, $p = .002$, $\eta^2 = .095$, with Geisser-Greenhouse correction (see Table 1 and Figure 3). Analogous to the results in number line studies (Booth & Siegler, 2006; Siegler & Opfer, 2003; Siegler, Thompson & Opfer, 2009), 6-8-year-olds had higher nonlinearity scores than 9-11-year-olds and adults (see Table 1). A significant age effect was also found for the PAE, $F(2, 136) = 6.03$, $p = .003$, $\eta^2 = .206$.

In terms of variance, 6-8-year-old children showed the most variable estimates, but the age difference for variance did not reach statistical significance (see Table 1). As Figure 2b shows, the CV decreased logarithmically as the target interval increased across the age groups (for 6-8-year-olds, $B = -.593$, $F(1, 27) = 167$, $p < .001$, $R^2 = .861$; for 9-11-year - olds, $B = -.782$, $F(1, 27) = 682$, $p < .001$, $R^2 = .962$; and for adults, $B = -.613$, $F(1, 27) = 259$, $p < .001$, $R^2 = .905$), which indicates that the scalar property was violated. This logarithmic decrease was not compatible with the sub-second interval perception literature (e.g., Allan & Gibbon, 1991; Droit-Volet, 2002; Droit-Volet, Clement, & Wearden, 2001). However, Lewis and Miall (2009) used a similar range of interval and observed the same logarithmic decrease in CV with an increasing target interval, which indicates that people may have relied on different timing mechanisms according to the range of target intervals.

Moreover, some studies have noted several conditions that generate a logarithmic decrease in the CV. For example, people usually use a counting strategy for estimating intervals greater than approximately 1.2 s (Grondin, Meilleur-Wells, & Lachance, 1999; Killeen & Weiss, 1987); this strategy results in a decrease in CV with increasing target interval (Wearden, 1991). In addition, Wearden and Lejeune (2008)

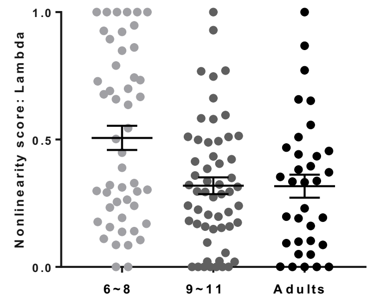

Figure 3. Distribution of nonlinearity score across age groups

reviewed the temporal distance perception literature and revealed that verbal estimation studies reported a decrease in CV with increasing target interval, as well as a similar pattern of mean estimates, similar to the current study. That is, the participants tended to overestimate short intervals and underestimate longer intervals (e.g., Penton-Voak et al., 1996; Wearden et al., 1998). To sum up, although the variation distribution in the current study did not follow the scalar property, it still showed a continuous pattern without breakpoints. These results imply that across age groups and intervals (1s - 180s), the participants might rely on one common mechanism for timing the intervals.

The effect of previous estimates. In the number line study literature, Cicchini, Anobile, and Burr (2014) claimed that the logarithmic estimate comes from the participants' decision bias, such as the central tendency of judgments. That is, under conditions of uncertainty, people's responses tend to be biased toward the mean of the stimulus distribution, and this regression to the mean predicts a logarithmic pattern of results for the number line task (Cicchini, Anobile & Burr, 2014). Cicchini and colleagues (2014) suggested that trial-by-trial online updating, which they called "dynamic encoding," should exist, supporting the regression to the mean. Thus, we tested whether any serial dependencies exist between the response to the current trial and the temporal distance between the current and previous trials; to do this, we explored the potential cause of the nonlinear mapping of the temporal estimates.

For our analysis, we regressed the average error of the estimate against the temporal distance between the current target interval and the previous one. We found that when a previous time point was further in the past, the participants tended to underestimate the current target interval; when a previous time point was further in the future, they tended to

Table 1

Means and Standard Deviations of the Nonlinearity Score, PAE, and CV in Experiments 1 and 2.

	Age group	(Condition)	Nonlinearity score (λ)	PAE	CV
Exp. 1	6-8-year-olds		.507 (.331)	.216 (.053)	.395 (.049)
	9-11-year-olds		.319 (.246)	.181 (.039)	.443 (.065)
	Adults		.317 (.246)	.159 (.032)	.430 (.064)
Exp. 2	Adults	Dispersed	.199 (.231)	.152 (.035)	.246 (.074)
		Clustered	.378 (.293)	.182 (.053)	.283 (.086)

overestimate it. The mean error of the temporal estimate changed systematically as a function of the temporal distance between the current and previous target intervals across the age groups (for 6-8-year-olds, B = -.278, F(1, 56) = 179, p < .001, R^2 = .762; for 9-11 year olds, B = -.176, F(1, 57) = 231, p < .001, R^2 = .802; and for adults, B = -.264, F(1, 56) = 77.5, p < .001, R^2 = .58). Thus, the estimated interval was influenced by the previous target interval, which tends to anchor the next estimate. This strategy might have resulted in the logarithmic pattern of estimation as Cicchini et al. (2014) argue. Furthermore, the participants who relied more on a "dynamic encoding" strategy showed higher error (B = .186, F(1, 137) = 44.3, P < .001, R^2 = .245) and higher non-linearity in their estimates (B = 1.5, F(1, 137) = 100, p <. 001, R^2 = .422) than those who relied less on this strategy. The central tendency seemed to have the effect of increasing the non-linearity of the estimates.

Experiment 2

In Experiment 2, we aimed to address two main issues. The first one was how remembering and estimating temporal information of natural events compared across prospective and retrospective paradigms. When previous research results on temporal distance perception (e.g., Brown, 1985; Miller, Hicks, & Willette, 1978; see Zacks et al., 2007 for review) are generalized to timeline estimation, the estimates of prospective judgments would be larger than those of retrospective judgments.

The second issue we addressed in Experiment 2 was how different event structures create different effects on timeline estimation. Using classical temporal distance perception paradigms with simple tones, Matthews (2013) demonstrated that increasing the subdivision of the interval by adding more markers led to increases in the perceived temporal distance. Zacks and his colleagues (2007) suggested that perceptual systems split activity spontaneously into segments, which enable people to treat an extended interval of time as a single chunk and serve as anchors in long-term memory encoding (Kurby & Zacks, 2007). If these two effects apply to timeline estimation with natural stimuli, we hypothesize that the participants would break a video clip into subjective sub-events, and each sub-event would then be used as a chunk to estimate the temporal distance of the video; accordingly, a video with more subjective sub-events would result in prolonged distance perception and distort the relation between the estimates and stimulus distances.

To address these two issues, we manipulated the instructions and contents of the video clips during the initial learning phase. In the first block examining retrospective timing, we asked the participants to pay attention to the contents of the video, but the participants were unaware that they would later be asked to make temporal judgments about the video. In the second block examining prospective timing, we informed the participants before the learning phase that they would be asked the same questions as in the first block, enabling them to pay attention to temporal information. We expected them to actively track the passage of time while they viewed the video.

To investigate the event structure effect on timeline estimation, we presented two different video clips with different numbers of sub-events and distributions. Using the subjective event segmentation procedure (Newtson, 1973), we asked a separate group of participants to mark points on the timeline where significant changes occurred in the video clip. Then, we chose two video clips with the most marked and the least marked and used them as stimuli in the learning phase. The video clip marked with the largest number of sub-events was 'Clustered' so that the marks were clustered near the beginning of the video. The video clip marked with the smallest number of sub-events was 'Dispersed' so that the marks were evenly distributed throughout the video.

Method

Participants Twenty-two undergraduates at the Ohio State University participated in exchange for a course credit, and 10 young adults from Daegu, South Korea, were recruited and participated with $4.70 compensation. There was no significant difference in performance between these two groups (T = 0.2).

Materials and Procedure. Two blocks of the timeline task were given to the participants. At the beginning of the second block, we informed them that after the learning phase, they would be given the same temporal judgment task as in the first block. To manipulate the event structure, we provided the two different video clips that were described above. The order of the video clips was counterbalanced across the participants. We created 30 still pictures from each six-second interval of the video clip and randomly presented all of the pictures three times during the testing phase. Thus, the total number of trials in the testing phase was 90. The other procedures were the same as in Experiment 1.

Results and Discussion

First, as in Experiment 1, an increase in the target interval resulted in an increase in the participants' mean estimates and a logarithmic decrease in the CV (B = -.78, F(1, 28) = 195, p < .001, R^2 = .874). That is, the scalar property was still violated. The participants' estimates showed serial dependence on the previous target distance across the two

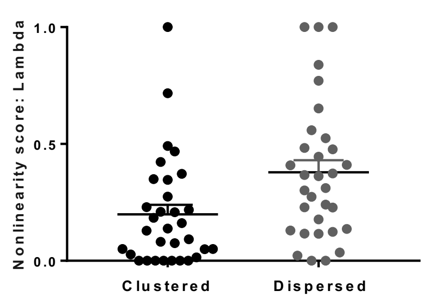

Figure 4. Changes in the distribution of the nonlinearity score according to the event structure of stimuli.

video clips (for Dispersed, B = -.125, F(1, 58) = 111, p < .001, R^2 = .658; for Clustered, B = .-184, F(1, 58) = 284, p <. 001, R^2 = .83). This finding indicates that the participants in Experiment 2 might have used the dynamic encoding strategy like the participants as in Experiment 1. Furthermore, the participants who relied more on the dynamic encoding strategy showed less accurate (B = 2.38, F(1, 30) = 114, p < . 001, R^2 = .792) and more variable estimations (B = .304, F(1, 30) = 34, p < .001, R^2 = .531) than those who did not. The use of a dynamic encoding strategy was also significantly related to the nonlinearity of the estimates (B = .368, F(1, 30) = 14.2, p < .001, R^2 = .321).

Next, we observed an effect of the event structure on the timeline estimation accuracy, T(31) = -3.49, p = .001, Cohen's d =-.616, but not on the variability distribution, T(31) = -1.89, p = .068 (see Table 1). The distribution of the nonlinearity scores was significantly different between the two types of video, T(31) = 2.81, p = .009, Cohen's d = .497. Specifically, the participants showed a more non-linear pattern of estimation when they were shown a video with clustered events (see Figure 4). As Matthew (2013) suggested, the clustered event distribution of the initial time period might have led the participants to overestimate the distance of the initial events, and the relatively sparse event distribution of the final time period would have resulted in the underestimation of it.

As some participants watched a "Clustered" video in the first block and the other participants watched a "Dispersed" video in the first block, the block effect (i.e., retrospective vs. prospective timing) was tested separately for each video type. However, the block order did not produce any significant differences in the accuracy [$T_{Dispersed}(19.2) = .263, T_{Clustered}(24.5) = .703$, with the Welch correction] or variation of the estimates [$T_{Dispersed}(25.2) = .364, T_{Clustered}(29.2) = .212$, with the Welch correction] across the video types. Of course, we should caution not to conclude too much from these null results because the current experimental structure cannot separate the retrospective/prospective timing effect from the practice effect due to block order.

However, some authors have shown that retrospective judgments can become as accurate as prospective judgments when using natural coherent events (Boltz, 2005) and long intervals with verbal estimates (Grondin & Laflamme, 2015). According to our results, we suggest that retrospective and prospective timing effects may have occurred in only the sub-second interval range. Similar to previous findings showing the violation of the scalar property in specific ranges of temporal distance (see Wearden & Lejeune, 2008, for review), the timing process effect may have occurred in a specific range of intervals. This conjecture could be a research question for further studies.

General Discussion

The main purpose of the present study was to introduce a novel timeline estimation task and explore its potential impact. This procedure examined both temporal distance perception and temporal order memory for the same task using realistic stimuli. To the best of our knowledge, this is the first examination of these two types of temporal processes using the same procedure *with non-linguistic temporal stimuli*[1]. We also extended several findings of previous interval perception studies and reported novel findings on development in temporal processing.

Specifically, in Experiment 1, we conducted a timeline estimation task with three different age groups – 6-8-year-olds, 9-11-year-olds, and adults – and observed that the accuracy and linearity of temporal estimation increased with the participants' age, while the variability decreased. Specifically, all of the age-related changes in the current study were observed between ages 8 and 9, which provides further evidence for the protracted development of temporal cognition (Friedman & Laycock, 1989; Friedman & Lyon, 2005; Gosse & Roberts, 2013; Pathman et al., 2013; Pathman & Ghetti, 2014; Zelanti & Droit-Volet, 2011). Because it does not rely on specific time words, such as before, after, minutes, and seconds, even preschoolers can perform the tasks, which could enable us to compare various age groups within the same experimental paradigm in the future.

In Experiment 2, we tested the effect of event structure on timeline estimation and extended Matthew's (2013) results to this novel temporal judgment task. As in the simple tone distance task (Matthew, 2013), the participants overestimated the intervals with more sub-events, which resulted in more distorted mapping between the estimates and target intervals. This parallel finding suggests that our timeline task is appropriate for investigating temporal distance and order judgments.

Another strength of our task is that any ranges of time or types of stimuli could be given to participants in the learning phase. As in the current study, clips from commercial movies with various lengths can be used to test the participants' efficiency in temporal judgment. It is also easy to manipulate either the contents or structure of the stimuli. Thus, this task could be more realistic than previous temporal distance perception tasks with simple tones, and it could be controlled better than other biographical memory tasks with individual experiences. To sum up, this novel timeline task would be a valuable tool for many researchers in uncovering developmental and individual differences in integrated temporal processing.

[1] We thank Tyler Marghetis for informing us of a recent study that used a similar timeline task with linguistic stimuli (Tillman et al., 2017).

Acknowledgments

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