Temporal bisection in 4-month-old infants

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ABSTRACT

The present study was the first to investigate infants’ ability to discriminate time using a bisection task that has been extensively used with animals and human adults. Infants aged 4 months were presented with two standard auditory signals, one short (S = 500 ms) and one long (L = 1500 ms), and were trained either to look to the left after S and to the right after L, or vice versa. During the test phase, the infants were then presented with intermediate durations without reinforcement as well as the two reinforced standard durations, for which the reinforcement was either immediate or delayed of 3 s. The times spent by the infants looking to the right, left or away from the target after the stimulus duration were coded by two "blind" coders. The results revealed an orderly psychophysical function with the proportion of long responses increasing with signal duration. The point of subjective equality (Bisection Point) was closer to the geometric mean of the short and long standard duration than to their arithmetic mean. A modeling of our data using the scalar timing models revealed that the infants in our study had a relatively high sensitivity to time but that their time performance was affected by the fact that they made a large number of random responses. The development of the perception of time will be discussed in the light of similarities and differences in temporal bisection performance between different species (rats and humans) and the different levels of development observed within a given species.

Key words: Time, Time perception, Infant, Bisection
INTRODUCTION

In 1977, Church and Deluty published an experimental study in which a new method was developed to examine temporal abilities in animals. The authors referred to the method as "temporal bisection". In their study, 8 rats were initially trained to press a lever on the left after a short signal duration (e.g., 1 s) and a lever on the right after a long signal duration (e.g., 4 s). Correct responses were reinforced by food. During the test phase, the rats heard probe signals of unreinforced intermediate durations, while the training conditions were also maintained by means of the two reinforced anchor-signal durations. During the test phase, the rats pressed the “long” lever more often in response to the longer signal durations. They thus generated an orderly psychophysical function, with the probability of a “long” response (p(long)) increasing with signal duration. According to Church and Deluty (1999), “these results on temporal discrimination suggested that the rat has some sort of internal clock that it can read” (p.223).

Fourteen years after this pioneering work, Wearden (1991) and Allan and Gibbon (1991) decided to use a temporal bisection procedure in human adults similar to that already used in animals. However, it was necessary to adapt the bisection task for use with humans. Three major procedural changes were introduced. The first procedural change took the form of using verbal instructions for human adults. Allan and Gibbon (1991) told their participants (N = 6) to categorize each signal duration as either short or long, while Wearden (1991) told them to judge whether the signal duration was more similar to the short or to the long standard duration. The second procedural change involved the number of trials required to obtain an orderly bisection curve, with several days of training being required for animals and only a small number of trials for human adults. The third procedural change related to the duration values used. Whereas Church and Deluty (1977) used duration ranges of several seconds, both Allan and Gibbon (1991) and Wearden (1991) used durations shorter than 2 s.
The reason was to avoid complications arising from the use of counting strategies by humans (for a review, see Clément & Droit-Volet, 2006). However, since the completion of these initial studies, longer durations have been tested in bisection studies involving human adults (e.g., Penney, Gibbon, & Meck, 2000; Wearden, Rogers, & Thomas, 1997). Despite the different procedural variants used in human bisection, the performance achieved by adults is close to that observed in animals. Considering the robust nature of human bisection performance, Wearden (1991) concluded that humans possess a mental clock system that is in many ways similar to that found in animals.

More recently, McCormack, Brown, Maylor, Darby and Green (1999) and Droit-Volet and Wearden (2001) decided to investigate the ontogenetic development of temporal bisection behavior. The former tested children aged from 6 to 10 years while the latter studied children aged 3 to 8 years. The slope of the bisection curves obtained for children was seen to increase with age, thus indicating an age-related improvement in time sensitivity, with the slopes becoming similar to those of adults at 8 and 10 years of age (e.g., Droit-Volet, Tourret, & Wearden, 2004; Droit-Volet, Meck, & Penney, 2007; Rattat & Droit-Volet, 2001, 2005). Although flatter in the younger children, the psychophysical functions appeared orderly in children as young as 3 years of age. However, the bisection procedure used with the school-age children was very similar to that used in adults, and was therefore largely based on verbal instructions. This kind of procedure makes it impossible to examine early temporal bisection behavior in non-verbal infants. The purpose of the present study was to develop a method for studying temporal bisection in infants. This issue is important since we currently possess little knowledge about infant’s ability to measure time and how the development of cognitive abilities affects time perception.

The main difficulty in investigating infants' abilities in time perception lies in the difficulty of developing a procedure that is suitable for use with non-verbal children (for a
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review, see Droit-Volet, Delgado & Rattat, 2006). Conventional time conditioning has been successfully used in infants when studying autonomic nervous system responses, such as heart rate or pupillary diameter (Abrahamson, Brackbill, Carpenter, & Fitzgerald, 1970; Brackbill & Fitzgerald, 1972; Colombo & Richman, 2002). Moreover, infants have been seen to regulate their answers over time in response to temporal reinforcement conditions. In their study, Darcheville, Rivière and Wearden (1993) suggested that infants aged between 3 and 23 months could delay touching a touchscreen in response to a fixed reinforcement interval (FI) of between 10 and 80 s. Infants have also been found to be able to increase the intervals between bursts of non-nutritive sucking in order to listen to music (Droit, Provasi, & Pouthas, 1993; Pouthas, Provasi, & Droit, 1996).

More recently, VanMarle and Wynn (2006) investigated the ability of infants to discriminate event durations. Six-month-old infants were habituated to a complex auditory-visual event located in the center of a display for a standard duration (either 2 or 4 s). More precisely, during the timecourse of the standard duration presentation, a puppet (Sylvester the cat) moved his head from right to left while producing a sound. In the test phase, the infants were then presented with the same event for 2 and 4 s alternately. When the puppet's activity stopped, a hidden observer monitored the infants’ looking time. The results showed that the infants looked at the puppet for longer after the new duration than after the old duration. This finding is consistent with the results obtained by Brannon and her co-workers (Brannon, Roussel, Meck, & Worldorff, 2004; Brannon, Libertus, Meck, & Worldorff, 2008), which indicated a difference in the amplitude of negative polarity (mismatch negativity) of neural activity in 10-month-old infants’ brains when they detected a temporal deviation in a stream of tones produced with a regular 1500-ms inter-stimulus interval. To summarize, the infants’ reactions of surprise to the cessation or continuation of the puppet’s activity or to changes in temporal rhythm suggest that event duration is a critical dimension processed by infants.
To further investigate the various temporal abilities exhibited by infants in the processing of event durations, we decided to adapt the bisection procedure for use in infants. In our study, infants aged 4 months were presented with the two standard auditory signals, one short (S = 500 ms) and one long (L = 1500 ms). They were then trained to look to the left after S and to the right after L or, conversely, to the right after S and to the left after L. The correct response was reinforced immediately by the appearance of a colored picture on the appropriate side of a panel. During the test phase, the infants were then presented with non-reinforced intermediate durations and the two reinforced standard durations, for which the reinforcement was either immediate or delayed by 3 s. Since infants find it difficult to remain vigilant during a long session, we decided to use 3 instead of the 5 intermediate durations conventionally used in bisection tasks involving children and adults.

Method

Participants

The final sample consisted of ten 4-month-old infants (5 girls and 5 boys; mean age: 4.06, SD = .26). Their parents were given a consent form to read and sign. Three additional infants were excluded from the final sample because it was impossible to calculate a bisection point and a Weber ratio for their psychophysical functions.

Materials

Each infant sat in a commercially available travel seat placed on the floor 80 cm in front of a square white wooden panel (85 X 100 cm) on which visual stimuli were projected by means of a video projector placed on a 30 cm raised support located on the floor behind the infant. The video projector was connected to a Power Macintosh computer that controlled all experimental events via the PsyScope program (Cohen, McWhinney, Flatt, & Provost, 1993). The auditory temporal stimuli consisted of animal cries (60 db), e.g. a quacking duck. The visual stimuli, which served as reinforcements, took the form of eight colored pictures
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(e.g., a boat or a rattle). These pictures were projected at a visual angle of approximately 15° and appeared approximately 18° to the left or right of the infant's center of vision. Left and right speakers connected to the computer were placed on either side of the infant’s head. Eye movements were recorded using a digital video camera (Sony DCR-HC 38) which was positioned just behind a hole of 3 cm diameter located in the middle of a wooden panel. A time-coded picture of the infant’s eyes together with an associated audio track generated by iMovie were used to code the infant's gaze as looking toward the left, right or away from the display panel during the 3 s following the end of the auditory stimulus.

Procedure

Each infant performed a bisection task which was divided into three successive phases: pretraining, training and testing. Pretraining consisted of 10 trials, i.e. 5 short trials and 5 long trials. In the "short trials", the infants were presented with the short standard duration (500 ms) which was immediately followed by the presentation of a single picture - randomly chosen among the eight pictures. Similarly, in the "long trials", the infants heard the long standard duration (1500 ms) immediately followed by the presentation of a single picture on the other side of the panel. The assignment of the short and the long standard durations to the left and the right sides of the panel was counterbalanced across the infants.

During the training phase, the infants were trained to look at the side of the panel (right or left) associated with the previously presented standard duration. All the infants performed 20 trials, with reinforcement being immediate in 10 trials (“unanticipated trials”) (5 for each standard duration) and delayed by 3 s in the other 10 trials (anticipated trials) (5 for each standard duration). These trials were presented in random order. The unanticipated trials were therefore similar to those encountered during pretraining. In the case of the anticipated trials, there was a 3 s delay between the end of the standard duration and the
appearance of the reinforcement (i.e., the picture). The times spent looking to the right, left or away from the panel were coded only for anticipated trials, i.e. during this 3 s delay period.

Finally, during the test phase, each infant performed 30 trials: 5 short and 5 long unanticipated trials, 4 short and 4 long anticipated trials, and 12 non-reinforced intermediate trials (4 for each intermediate duration: 750 ms, 1000 ms and 1250 ms). In the case of the non-reinforced intermediate trials, the infants were presented with one of the three intermediate durations followed by a 3 s delay period after which no picture was projected on the panel. The different stimuli within this phase were presented in a random order although it was not possible for there to be more than 3 consecutive non-reinforced intermediate trials. Times spent looking to the right or left or away from the panel were coded for both anticipated trials and non-reinforced intermediate trials.

RESULTS

The analyses were conducted on the proportion of time spent looking at the side of the panel associated with the long standard duration during the 3 s following the end of the stimulus presentation. For each trial, a “long” response was counted when the looking time for L was higher than the looking time for the other side of the panel which was associated with S or the time spent looking way from the panel. Two independent “blind” coders performed a step-by-step recoding (30 images/second) of the video recording on the basis of a visual cue which indicated the end of the stimulus duration. However, the recording was played without sound in order to make it impossible to identify the type of stimulus duration perceived by the infant. The level of agreement for the proportions of “long” responses between the two coders were 0.78 and 0.88 for the 500-ms and the 1500-ms anticipated standard duration trials respectively and 0.76, 0.74, and 0.80 for the 750-ms, 1000-ms, and 1250-ms non-reinforced intermediate duration trials respectively.
Figure 1 presents the psychophysical function obtained by the 4-month-old infants with the mean proportion of 'long' responses \( p(\text{long}) \) plotted against the signal duration. This psychophysical function appears orderly. Indeed, the ANOVA\(^2 \) run on \( p(\text{long}) \) with the signal duration as within-subject factor revealed a significant effect of signal duration, \( F(4, 36) = 16.21, p = .0001 \), thus indicating a steep bisection function with \( p(\text{long}) \) increasing with the signal duration values. The effects of sex and S-L presentation order were not significant (all \( p > .05 \)). In addition, the bisection curve had an ogival appearance, with a bisection point (BP) closer to the Geometric Mean (GM) of S and L (i.e., 866) than to the Arithmetic Mean (AM) (i.e., 1000). The BP, also called the point of subjective equality, is the signal duration which results in the same frequency of short and long responses \( p(\text{long}) = .50 \). In the present study, the BP was derived from the fitting curve, obtained by means of a logarithmic regression, that provided the best fit with the data-group curve, Figure 1, \( R^2 = .98, p = .002 \). The BP derived in this way was 854, a value which is indeed closer to the GM than to the AM of S and L. This BP value was close to the mean of the individual-subject BP \( (m = 860, SD = 177) \). A Weber Ratio (WR) was also derived from this fitting curve. This is an index of temporal sensitivity: The higher the WR, the lower the infant's sensitivity to time is. The WR corresponds to half the difference between the stimulus giving rise to \( p(\text{long}) = .75 \) and that giving rise to \( p(\text{long}) = .25 \), divided by the BP. The WR calculated here was .39 which was close to the mean individual-subject WR \( (m = .32, SD = .13) \).

To gain a better understanding of infants’ bisection performance, we decided to model our data using the mathematical models proposed by Scalar Timing Theory (Gibbon, 1977; Gibbon, Meck & Church, 1984) for use with temporal bisection data. There are two main models, the Sample Known Exactly (SKE) model developed by Gibbon (1981) for animals and the Difference Modified (DM) model, which is a modification of an earlier model.
developed by Wearden (1991) to account for bisection performance in human adults. These models included two close parameters, $c$ and $\beta$. In these models, $S$ and $L$ are represented in the form of normal distributions of values with means equal to $S$ and $L$ together with a coefficient of variation, $c$. The $c$ parameter is the first parameter included in these models. It indicates the variability of the memory representation of the standard durations, and is thus considered to be a sensitivity parameter. An increase in its value flattens the psychophysical function slope, thus indicating a lower sensitivity to time (for an illustration, see Droit-Volet & Wearden, 2001). In these models, the decision to respond short or long is therefore based on the comparison of the distances between the duration, $t$, that has just been presented and the short standard duration and long standard duration, or, more precisely, a sample taken from the long-term memory of $S$ and $L$, namely $s^*$ and $l^*$ respectively. If the difference between $t$ and $s^*$, and $t$ and $l^*$ is too small, i.e., below a threshold $\beta$, the models respond long. $\beta$ is the second parameter in these models. It therefore represents a kind of bias toward reporting "long" when the differences are not clearly discriminated. Increasing the $\beta$ value shifts the center of the bisection curve toward the left. The coefficient of variability of the $\beta$ parameter has been shown to have little effect on the results (for a more detailed description, see Penney et al., 2000; Wearden et al., 1997). In the present study, it was fixed at zero.

Although the MD and the SKE models both make use of these two parameters, $c$ and $\beta$, they differ in the type of decision rule employed. The decision rule is based on differences in the MD model and on ratios in the SKE model. More precisely, the MD model responds long if $\text{Dif.}(s^*, t) > \text{Dif.}(l^*, t)$ and short if $\text{Dif.}(s^*, t) < \text{Dif.}(l^*, t)$. In contrast, the SKE model responds long if $(l^*/t) < (t/s^*)$, and vice versa. These two models were therefore both tested in the present study in order to account for the infants’ bisection performances. However, we added a third parameter, $p$, to both models in order to make it possible to account for temporal bisection in young children (e.g., Droit-Volet & Wearden, 2001; Droit-Volet & Izaute, 2009;
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Droit-Volet et al., 2004). This parameter corresponded to the probability of producing a response at random on each trial (i.e., “short” and “long” responses equally likely) irrespective of stimulus duration.

These two models, modified through the inclusion of the new $p$ parameter, were coded in a program written in Visual Basic 6.0, and run for 1,000 trials. $c$, $b$ and $p$ were varied over a wide range in order to obtain the best fitting simulation between our group data and our modeling data in terms of mean absolute deviation (MAD), i.e. the sum of the absolute deviations between our data and the simulated data divided by the number of signal durations judged. The modified MD model never provided any good fit with our data. The only solution to this would be to add a fourth parameter to reflect a major shortening effect in the memory representation of the two standard durations. However, such an addition finds little theoretical support in the literature on timing bisection. As discussed below, this inability to find a successful fit of the MD model to our data is due to the fact that this model produces a BP at the AM of the two standard durations rather that at their GM as was observed in the infants in our study. In contrast, the modified SKE model fitted our data reasonably well and produced an MAD of .03. Table 1 provides an overview of the values of the parameters used in our simulation. We observed that, at only .01, the $\beta$ value was particularly small as has previously been observed in both children and adults in cases where feedback has been provided during the bisection test phase (Droit-Volet & Izaute, 2009). The $c$ parameter value was .25, and was therefore similar to the values obtained for temporal bisection in animals (Meck, 1983). More specifically, the value of the $p$ parameter (.33) appeared to be particularly high. This $p$ value helped account for the high proportion of short responses (approximately 20%) for the longest signal duration, a proportion which is generally close to zero in animals and human adults. To summarize, the high level of noise in the infants’ responses masked - at least partially - their ability to process time.
DISCUSSION

Our pioneering study on temporal bisection in infants demonstrated that children as young as 4 months of age are able to discriminate between different signal durations in a bisection task. This is consistent with results found by Brannon et al. (2004, 2008) and VanMarle and Wynn (2006) using different temporal discrimination tasks in infants. However, the fact that the infants in our study were younger than those participating in these earlier studies (10 and 6 months) reveals a more precocious and fundamental ability to process the duration of events. Consequently, our results fill the gap between the temporal bisection performances observed elsewhere in animals, on the one hand, and children aged 3 years or more, on the other.

Despite differences in the procedures employed in the bisection tasks used for each animal species (rats, humans) and for each developmental level within a given species, the results obtained for time bisection systematically reveal orderly psychophysical functions, with participants responding long more often when the signal duration increases. This reveals the remarkably robust nature of temporal behaviors in bisection tasks, and also permits a more informed discussion of similarities and differences in bisection performance within a developmental perspective. Two major indexes were used to describe temporal bisection behaviors: the WR, i.e. an index of time sensitivity, and the BP, i.e. the point of subjective equality. As far as the WR is concerned, in the present study, the infants obtained a WR of .37, thus indicating that the slope of their bisection curves was relatively flat and their time sensitivity quite low. Although the WR values vary slightly as a function of experimental conditions, studies in rats have found an average WR of 0.23 within a range of 0.18 to 0.25 (e.g., Church & Deluty, 1977; Meck, 1983; Santi, Miki, Hoenyak, & Eidse, 2006). In human adults, the WR value has generally been found to be lower - at about .17 (range .13 to .20),
thus indicating a higher sensitivity to time (Allan & Gibbon, 1991; Droit-Volet et al., 2004; Wearden, 1991; Wearden et al., 1997). The WR of school-age children aged 8 to 10 years has been found to be close to that of adults (Droit-Volet et al., 2000; 2005; McCormack et al., 1999; Rattat & Droit-Volet, 2001, 2005). Before this age, the WR value is particularly high (between .30 and .40), thus suggesting a lower sensitivity to time. However, Droit-Volet and Izaute (2009) recently showed that when feedback was provided during the bisection test as in the present experiment, the WR values of 5 and 8-year-old children decreased (i.e., .26 and .23, respectively), while the corresponding level in adults did not change. To summarize, a genuine age-related improvement in sensitivity to time occurs between birth and the age of 8-10 years.

The question raised here is what is the reason for this improvement in temporal bisection sensitivity in the duration range tested in our study (< 2 s)? Is it due to the maturation of a basic neural mechanism involved in the encoding of time (for reviews, see Buomano, 2007; Ivry & Schlerf, 2008; Meck, Penney, & Pouthas, 2008; Witmann, 2009) or to other cognitive processes that interfere with bisection judgment and prevent the emergency of temporal behavior similar to that found in adults? Time sensitivity was evaluated on the basis of the bisection curve – i.e., a behavioral output in the form of a decision to respond short or long which results from a complex interaction between different cognitive processes, some of which being not directly related to time processing per se (Gibbon et al., 1984). The modeling of the data allows us to better identify the specific contribution of each of these processes to infants' time sensitivity. The simulation of our data using the modified SKE model revealed that the sensitivity parameter $c$ was .25, close to the value found in animals (e.g., average .25, Meck, 1983). This source of variation in time sensitivity, which is related to the representation of standard durations, was therefore similar in infants and non-human animals. We can therefore suppose that the basic mechanisms involved in the encoding of
time are enough physiologically mature to be functional in infants. In the present study, our model suggests that the specificity of the infants' psychophysical function slopes was due to the proportion of random responses that they produced irrespective of perceived duration. This major source of noise in their responses thus at least partially masked the infants’ sensitivity to short durations. However, it also suggests that a great number of internal and/or external factors might prevent infants from processing time accurately.

With regard to the BP, many bisection studies have attempted to localize this value (for a review, see Allan, 1998). In animals, the BP has systematically been found to be close to the GM rather than the AM of S and L. In contrast, and with few exceptions, the BP has systematically been found to be closer to the AM than the GM in human adults and children (Allan & Gibbon, 1991; Penney et al., 2000; Rodriguez-Girones & Kacelnik, 1995). As suggested above, the difference in BP localization between humans and animals was initially explained in terms of differences in the decision rule, with the former using a rule based on the difference between t, S, and L, and the latter using a ratio-based rule (Wearden, 1991). However, no clear theoretical rationale has as yet been provided for this change in decision rules. By investigating different temporal scales (linear vs. logarithmic) and different ratios between S and L, Wearden and Ferrara (1995, 1996) were able to demonstrate that the localization of the BP is mainly determined by the ratio between the two standard durations. A small ratio (< 1:2) - when it is not easy to distinguish between S and L - shifts the BP from the AM to the GM of S and L. This suggests that, in our study, the infants had more difficulty in bisecting durations with a larger ratio (1:3) than those that are required for children or adults. To provide evidence in support of this assumption, it now seems important to use different duration ratios to test bisection performance in infants.

Nevertheless, working with the same range of ratios, Droit-Volet and Izaute (2009) showed that the localization of the BP also varies as a function of the bisection procedure
used, i.e. when feedback is provided in the test phase as in the case of animals and when no feedback is provided as in the majority of studies involving human adults and children. Providing feedback in the test phase shifts the BP to the left and closer to the GM of S and L (Droit-Volet & Izaute, 2009). In addition, this changes the decision parameter, $\beta$ by decreasing its value to a level close to zero. In the bisection procedures used for infants and non-human animals, the $\beta$ parameter has been seen to be low, thus indicating no bias toward long responses. Finally, a major source of developmental changes in time bisection for short durations appears to lie not in the maturation of a neural timing mechanism which is functional at an early age (Brannon et al. 2004, 2008; Droit-Volet & Wearden, 2002), but rather in the development of decisional processes which are related to metacognitive development. As their metacognitive capabilities develop, participants question their feeling of knowing and the effectiveness of their strategies (Koriat, 1993). Participants therefore become aware that the intermediate signal duration in a bisection task is actually neither short nor long but that they are nevertheless obliged to respond (see Figure 2 in Droit-Volet & Izaute, 2009). The awareness of these ambiguous signal durations should therefore affect the bisection curve and the localization of the bisection point. In the developmental timing literature, there is growing evidence of a relationship between knowledge of time and decision strategies (Delgado & Droit-Volet, 2007; Droit-Volet, 2002; Droit-Volet & Izaute, 2005; Droit-Volet & Rattat, 2007; Montare, 1988; Rattat & Droit-Volet, 2005). Little is known about the role of decision strategies in time judgment (Wearden & Grindrod, 2003). Nevertheless, our study suggests that the developmental changes in decision strategy constitute the major source of age-related changes in the localization of the point of subjective equality in temporal bisection tasks.

Our pioneering study in temporal bisection showed that infants are able to discriminate short event durations, but also that their fundamental temporal abilities are
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masked by a number of factors, such as random responses. Moreover, our study demonstrated that the temporal bisection procedure can be used in infants to investigate their temporal abilities. To further investigate time bisection performance in infants, we must now test a variety of duration ranges and duration ratios.

FOOTNOTES

1. In France, children go to school at 3 years of age

2. The Mauchly test was not significant.

REFERENCES


d’Attraction Interuniversitaire.


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Table 1. The parameter values from the modified SKE model.

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<th>c</th>
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c = coefficient of variation of the memory representation of the short and the long standard durations; β threshold parameter; p = random response parameter; MAD = mean absolute deviation between the data points and the fits of the model.
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Stimulus durations (ms)

p(long)