Research Report

INFANT TIMEKEEPING:
Attention and Temporal Estimation in 4-Month-Olds

John Colombo and W. Allen Richman

University of Kansas

Abstract—*Four-month-old infants were exposed to sequences in which a 2-s light stimulus alternated with dark interstimulus periods whose length was manipulated to be 3 or 5 s. A predictable on-off pattern occurred for eight trials, but the light stimulus was omitted on the ninth trial. Infants showed heart rate responses on the omission trial that were closely synchronized with the expected recurrence of the stimulus. In addition, these heart rate patterns were observed predominantly in infants who had previously shown high levels of sustained attention in pretests with visual stimuli. These findings indicate remarkable precision in infants' estimation of time intervals, and suggest that the link between time estimation and attentional processes is present in early infancy.*

The perception of time has been an important topic in the history of psychology (Grondin, 2001; Montague, 1904), and the ability of humans and animals to estimate time is a fundamental line of inquiry in this area. The ability to perform accurate time estimation has been theoretically and empirically linked to attention (e.g., Boltz, 1991; Brown & West, 1990; Casini & Macar, 1999; Underwood & Swain, 1973; Zakay, 1989, 1993; Zakay & Block, 1996; Zakay, Block, & Tsal, 1999). Tasks requiring attentional effort interfere with the accuracy of time estimation (Brown, 1985; Curton & Lordahl, 1974; Fortin & Masse, 2000; Hicks, Miller, Gaes, & Bierman, 1977; McKay, 1977; Predebon, 1999; Sawyer, 1999; Von Sturmer, Wong, & Coltheart, 1968). In addition, children and adults with disorders of attention tend to perform poorly on time-estimation tasks (Barkley, Koplowitz, Anderson, & McMurray, 1997; Shaw & Brown, 1999; Sonuga-Barke, Saxton, & Hall, 1998).

Cognitive-neuroscience studies of time perception (Gibbon, Malapani, Dale, & Gallistel, 1997; Malapani, Dubois, Rancurel, & Gibbon, 1998) suggest that the same prefrontal and frontal cortex structures involved in sustained or *endogenous* attention (Duncan, 1995; Webster & Ungerleider, 1998) also likely mediate time estimation (Dietrich, Frederick, & Allen, 1997; Macar & Casini, 1998; Mimura, Kinsbourne, & O'Connor, 2000; Nichelli, Clark, Hollnagel, & Grafman, 1995; Rubia et al., 1998). One might expect, then, that the development of sustained or endogenous attentional components would parallel the development of accuracy in time estimation.

Time estimation has not been studied in infancy and early childhood, although temporal conditioning studies of human infants (e.g., Adkinson & Berg, 1976; Berg, 1974) are relevant to the topic. In such studies, infants are presented with predictable stimulus sequences followed by omission trials that violate such predictability. Nearly all these studies have reported significant heart rate (HR) responses to such omissions (e.g., Stamps & Porges, 1975; Stratton & Connolly, 1973; Turco & Stamps, 1980). The time course of the omission response might be taken to reflect the infant's estimation of time, but this has not been the focus of studies in this literature.

Two reports, however, do suggest that infants' HR responses to stimulus omissions may be temporally precise. Clifton (1974) tested newborns in a paradigm in which a conditioned stimulus (CS) preceded an unconditioned stimulus (US) by 2 s. After 30 trials of US-CS pairing, the US was omitted, and a large HR deceleration was observed beginning at the point in time that the US would have normally occurred. Donohue and Berg (1991) monitored 7-month-olds' HR response to two overlapping stimuli presented in a completely predictable sequence. In this study, the onset of white noise provided a cue to infants that a tone would occur in 10 s. The stimuli were paired for 17 trials, and then the tone was omitted for 3 trials. On the last of these 3 trials, an HR deceleration occurred at the point that the tone should have occurred.

Although these studies suggest that infants' time estimation might be quite accurate, in neither was the time course of the response the primary focus. Therefore, experimental controls that allowed definitive examination of the time course of the omission response were not included. The current study was designed to examine the precision of young infants' HR responses to stimulus omissions in different temporal sequences. In addition, it was designed to determine whether measures of the quality of infant attention might be related to the presence or timing of the HR responses to such omissions. Given that attention (particularly endogenous or sustained attention) has been linked with the accuracy of time perception, we hypothesized that individual differences in infants' sustained attention might be related to the accuracy of infants' estimation of time.

METHOD

Participants

Sixty-four 4-month-old infants (range: 119–126 days) were recruited by mail and telephone from the greater Kansas City metropolitan area. A total of 56 infants completed the attentional pretests, 52 completed the first eight stimulus trials, and 50 completed the entire protocol. Of the 14 infants who did not complete the session, 12 were fussy or had uncodable HR records (because of excessive movement), and 2 were lost because of equipment failure.

Apparatus, Stimuli, and Procedure

The infants were tested in a 2-m × 2-m booth, painted black on all walls and the ceiling. Centered on the wall facing them was a 1.0-m × 0.7-m translucent screen on which visual stimuli were rear-projected. The infants sat in a car seat 0.8 m from the screen.

After administration of informed consent, each infant was carried into the testing booth and placed in the car seat. The infant's HR was measured with shielded Ag-AgCl electrodes placed on either side of the chest and grounded with an unshielded electrode just above the navel. The electrocardiogram (EKG) was digitized at 250 Hz with an in-

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Address correspondence to John Colombo, Department of Psychology, 1415 Jayhawk Blvd., Fraser Hall, University of Kansas, Lawrence, KS 66045-7556; e-mail: colombo@ku.edu.

terface and a computer running commercial psychophysiological data-acquisition software (BioPac, Inc., Santa Barbara, California). This system was interfaced with a computer that provided time codes for stimulus and fixation events. After a clear EKG signal was obtained, the room light was dimmed gradually until it was completely off, and the infant sat in the darkened room with no stimulus while baseline HR data were collected for approximately 30 s.

Looking pretests

First, the infant's attention to a black-and-white slide of a female face and to a 10 × 10 checkerboard was measured. Both stimuli were presented at midline and subtended a visual angle of 20° horizontal × 16° vertical. Each stimulus was illuminated until the infant accumulated 20 s looking to the face and 10 s looking to the checkerboard. During the stimulus presentations, looks were coded on-line by a trained observer watching the session on video. The pretests were separated by a 3-s interval.

Timing sequence

A timing protocol began 15 s after the end of the second pretest. It comprised nine trials consisting of a blank slide (again 20° horizontal × 16° vertical) for 2 s and an interstimulus (IS) interval. Two conditions were produced by experimentally varying the IS interval length: 3 s (IS3) or 5 s (IS5). The regular on-off stimulus pattern occurred for eight trials. For both the IS3 and IS5 conditions, however, on the ninth trial the 2-s stimulus presentation was followed by a 15-s "off" period. This allowed us to examine the presence and time course of infants' HR reaction to the omission of the stimulus.

RESULTS

Pretests

HR data from the pretests allowed us to parse infants' looking during the pretests into three different HR-defined phases of attention (Richards, 1985): *orienting* (OR), *sustained attention* (SA), and *attention termination* (AT). Infant HR typically decelerates strongly (5–20 bpm) during looking. Richards (e.g., Richards & Casey, 1992) has argued that different segments of the HR deceleration reflect different levels of attention and information processing. SA has been repeatedly found to represent the period during which infants are least distractible and show the most robust stimulus recognition and discrimination, and is thus considered to reflect endogenous (i.e., voluntarily allocated and engaged) attention.[1]

Means, standard errors, and correlations for amounts of OR, SA, and AT during the pretests are presented in Table 1. Both SA and AT were significantly correlated across sessions, with the correlation for SA being particularly strong.

Timing Sequence

Infants' HR was calculated for 0.5-s epochs in each of the segments (stimulus and IS periods) of the timing sequence.

Response to stimulus onsets and offsets

During the blank-trial stimulus periods, infants showed a small (0.5 bpm) but statistically significant HR acceleration after stimulus onset, which diminished by the end of the 2-s period. A mixed-design Trial (8) × Epoch (4) × IS Condition (IS3 vs. IS5) multivariate analysis of variance (MANOVA) on infants' HR during the 2-s stimulus periods yielded only a main effect for epoch, $F(3, 43) = 9.31$, $p < .001$, with a significant quadratic component, $F(1, 45) = 24.51$, $p < .001$.

The length of the IS period differed for the IS3 condition (6 epochs) and IS5 condition (10 epochs). Thus, to conduct an omnibus analysis for these periods, we used a hierarchical linear modeling (HLM) approach.[2] The HLM analysis yielded significant main effects for all factors, but no interactions. Infants' HR decelerated (1.5 to 2.0 bpm, relative to initial levels) to stimulus offsets but then returned to initial levels; this yielded a significant effect of epoch, $F(9, 2816) = 2.22$, $p = .018$, that was characterized by a highly significant quadratic component, $F(1, 46) = 24.16$, $p < .001$. Infants' HR tended to increase linearly over trials, as indicated by a significant effect of trial, $F(7, 2816) = 3.33$, $p = .001$. Finally, infants in the IS3 condition had higher HRs than those in the IS5 condition, as indicated by a significant condition effect, $F(1, 2816) = 23.98$, $p < .001$.

Response to stimulus omission

The primary analysis of interest was the IS period for Trial 9. This analysis tested whether infants learned the temporal parameters of the eight-trial on-off stimulus sequence. The IS period for Trial 9 was 15 s (i.e., 30 epochs) long, but of most interest were those epochs before and after the time when the stimulus would have been expected to recur: the 6th epoch for the IS3 condition, and the 10th epoch for the IS5 condition. Therefore, data from the first 7 s (i.e., 14 epochs) of the omission phase were entered into an Epoch (14) × IS Condition (2: IS3 vs. IS5) mixed-design MANOVA. This analysis yielded a significant Epoch × IS Condition interaction, $F(13, 36) = 2.49$, $p < .015$; thus, the HR pattern across epochs was statistically different for the two conditions. Mean HRs for the stimulus period of Trial 8 and the first 7 s of the IS period of the omission trial are shown in Figure 1.

In both IS conditions, an HR acceleration began approximately 3 s before the expected stimulus onset. The acceleration was more pronounced in the IS5 condition (+4.3 bpm) than in the IS3 condition (+2 bpm), perhaps because the IS5 condition evoked a deceleration (−2 bpm) during the first 2 s of the period.

More interestingly, an HR deceleration was also observed in both the IS3 and IS5 conditions at or within 0.5 s of the point of the ex-

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[1] SA is defined as looking accompanied by HR at least 5 consecutive beats below a prestimulus median. Here, the prestimulus period was the 30-s baseline before the start of the pretests. OR was defined as that period of looking prior to the attainment of SA (i.e., the latency to decelerate), and AT was defined as looking that continued after SA, but during which HR returned to at least the prestimulus level. We encountered varying numbers of looks in which no SA could be coded. Because attention cannot be parsed without the attainment of SA (i.e., logically, neither OR nor AT is coded unless SA occurs), if SA was not observed within a particular look, we excluded it from our analyses.

[2] If the two IS conditions are analyzed in separate mixed-design MANOVAs, the results are the same as those reported.

Table 1. *Means (in seconds), standard errors, and correlations for total amount of time spent in the various attentional phases across the two pretests*

	Face		Checkerboard		Total		Cross-pretest correlation
Attentional phase	Mean	*SE*	Mean	*SE*	Mean	*SE*	
Orienting	1.71	0.31	0.19	0.06	1.90	0.33	.221†
Sustained attention	7.36	0.82	2.86	0.46	10.22	1.15	.615***
Attention termination	1.25	0.26	0.43	0.16	1.68	0.34	.285*

$^{\dagger}p < .10$. $^{*}p < .05$. $^{***}p < .001$.

pected recurrence of the stimulus. The magnitude of the deceleration was about 2 bpm, and the deceleration lasted approximately 1 s in both conditions. After this deceleration, the infants' HR was unremarkable; an Epoch × IS Condition MANOVA on HR after the 14th epoch (i.e., 7 s into the IS period) yielded no significant terms.

Individual differences in attention and omission responses

The final analysis tested the possible interrelation between individual differences in infants' endogenous attention (i.e., SA observed during the looking pretests) and the omission responses seen during the IS period of Trial 9. For this analysis, we first divided infants into high- and low-SA groups with a median split. We then "lined up" the time course of the infants' HR responses to the stimulus omission by synchronizing them at the point where the stimulus would have occurred (see Table 2). A mixed-design MANOVA with within-subjects factors of response (2: accelerative vs. decelerative) and epoch (5), and between-subjects factors of IS condition (2) and SA level (2: high vs. low), was then conducted. This analysis yielded a significant Response × Epoch × SA Level interaction, $F(4, 43) = 3.11$, $p = .025$ (see Fig. 2).

The high-SA group showed a robust acceleration (+3 bpm) and deceleration (−4 bpm) that straddled the point at which the stimulus would be expected to recur. The low-SA group showed neither response (+2 bpm and +1 bpm across the equivalent respective epochs). We decomposed the interaction by running Epoch × Response × IS Condition MANOVAs separately for the high- and low-SA groups; the analysis for the low-SA group yielded no significant terms, but the analysis for the high-SA group yielded a significant Response × Epoch interaction, $F(4, 19) = 3.44$, $p = .028$.

High-SA infants also had significantly higher ($p < .05$) AT levels than low-SA infants (see also Colombo, Richman, Shaddy, Greenhoot, & Maikranz, 2001). Thus, it was possible that the relationship between SA and HR omission responses was confounded by AT. To ad-

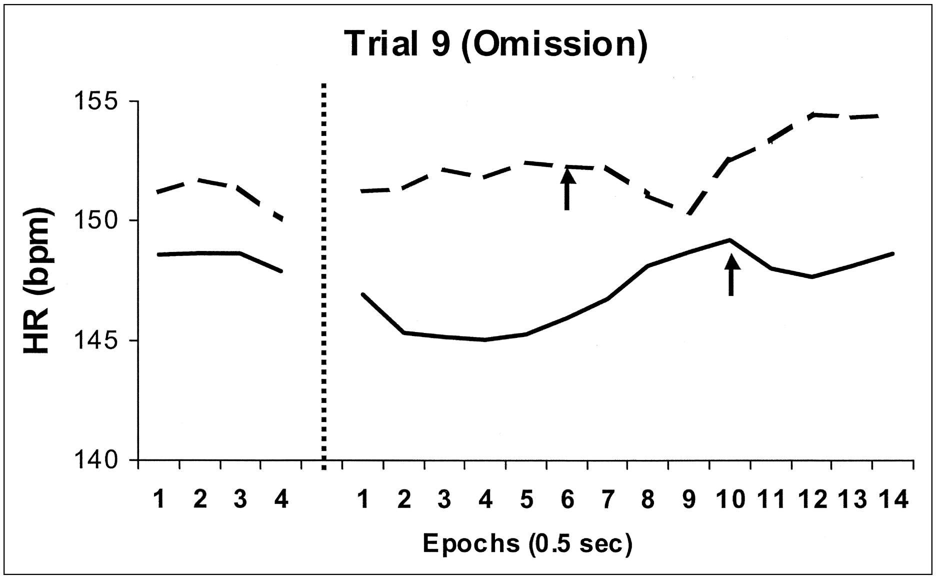

Fig. 1. Infants' heart rate (HR) during the stimulus period of Trial 8 (to the left of the vertical line) and the interstimulus period of Trial 9 (in which the stimulus presentation was omitted) for the two interstimulus (IS) conditions: IS3 (dashed line) and IS5 (solid line). The arrows show the points at which the missing stimuli would have occurred in the two conditions.

Table 2. *Synchronization of heart rate acceleration and deceleration phases on the omission trial for the two interstimulus (IS) conditions*

	Acceleration epochs					Deceleration epochs				
Condition	1	2	3	4	5	1	2	3	4	5
IS3	1	2	3	4	5	6	7	8	9	10
IS5	5	6	7	8	9	10	11	12	13	14

Note. Each response (accelerative and decelerative) was composed of five 0.5-s epochs. However, both responses were delayed in IS5, relative to IS3, by 2 full seconds. The table shows which of the 0.5-s epochs (starting from the offset of the stimulus on Trial 9) served as the first through fifth epochs for the two responses.

dress this possibility, we repeated the analysis substituting high- and low-AT groups for high- and low-SA groups, and the three-way Response × Epoch × AT Level interaction was not significant, $F(4, 43) = 0.50$. In addition, the critical three-way interaction for the SA analysis remained statistically significant ($p < .05$) even when the amount of AT was entered as a covariate. Both findings discount the possibility that AT levels confounded the relationship between SA and HR.

DISCUSSION

In summary, the results of this study indicate that young human infants show precise sensitivity to temporal parameters. When a stimulus was omitted from a predictable stimulus-stimulus sequence, an HR deceleration was observed remarkably close to the point at which a stimulus should have recurred. The differentiation of timing in the two IS conditions in this study provides the necessary control for inferences about infants' time estimation that cannot be drawn from previous studies of omission effects in infants (Clifton, 1974; Donohue & Berg, 1991). The finding that young infants can accurately estimate the length of brief intervals of time has important implications for contiguity-based aspects of learning and conditioning early in life (Colombo, 2001a).

In addition, these omission effects were most evident in the responses of infants who showed high levels of SA during the looking pretests. Richards (1985, 1997; Richards & Casey, 1992) contended that SA represents a voluntary maintenance of attention, during which infants are actively engaged in encoding and information processing. This assertion is supported by a considerable amount of evidence (see Colombo, 2001b). The extant data on time estimation in children and adults clearly suggest that the ability to keep accurate track of time is dependent on the allocation of attentional resources. In this study, those infants who showed higher amounts of such attention (i.e., SA) during attentional pretests were those who showed precisely timed HR responses to the omission of the stimulus on the ninth timing trial. Thus, the findings support the hypothesis that attention plays a role in accurate timekeeping in infancy, and suggest that an attentional model of time estimation or perception may be validly applied to young human infants, as well as children (Zakay, 1992) and adults (Block, Zakay, & Hancock, 1999).

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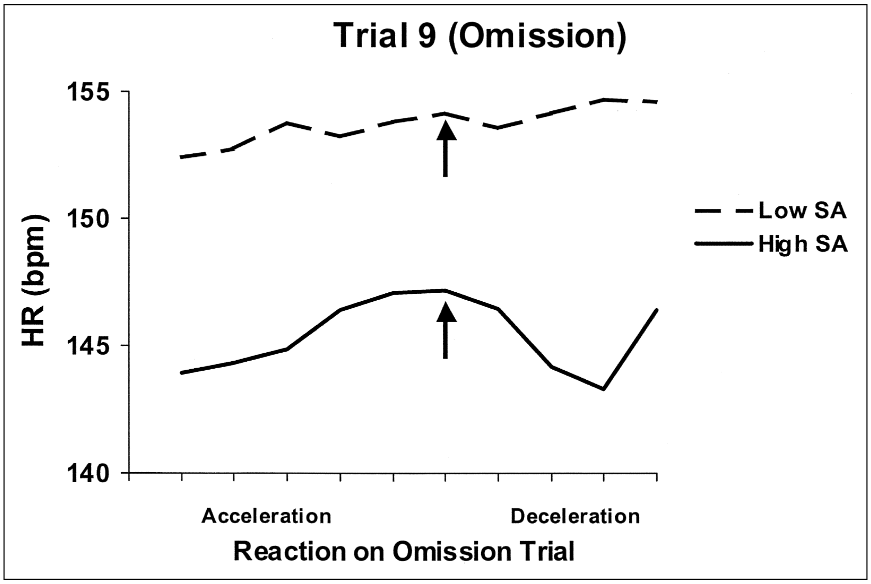

Fig. 2. Heart rate (HR) acceleration and deceleration during the interstimulus period on Trial 9 (the omission trial) for the high- and low-SA (sustained attention) groups. The arrows show the points at which the missing stimuli would have occurred in the two conditions.

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