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Temporal pattern and spectral complexity as stimulus parameters for eliciting a cardiac orienting reflex in human fetuses

LYNN J. GROOME
University of South Alabama, Mobile, Alabama

DONNA M. MOONEY
University of Arkansas, Fayetteville, Arkansas

SCHERRI B. HOLLAND, YOLANDA D. SMITH, and JANA L. ATTERBURY
University of South Alabama, Mobile, Alabama

and

ROSCOE A. DYKMAN
University of Arkansas, Fayetteville, Arkansas

The purpose of this study was to determine whether temporal pattern and/or spectral complexity were important stimulus parameters for eliciting a cardiac orienting reflex (OR) in low-risk human fetuses. Each of 28 term fetuses was exposed to four sounds formed from the four different combinations of temporal pattern (pulsed, continuous) and spectral complexity (sine wave, /å/). The fetal cardiac electrical signal was captured transabdominally at a rate of 1024 Hz, and fetal R-waves were extracted by using adaptive signal-processing techniques. We found that pulsed sounds elicited a significantly greater decrease in heart rate (HR) than did continuous sounds. However, the HR response was relatively unaffected by spectral complexity. For the pure tone and the phoneme used in this study, our results indicate that temporal characteristics were more effective at eliciting a cardiac OR in human fetuses than was spectral complexity.

Successful word recognition involves the perception and discrimination of different sounds, recall of a cognitive representation of specific sounds, and segmentation of speech into the correct sequence of words (Jusczyk, 1993). Although these skills are acquired at different times during development (Jusczyk, 1993), it appears that newborn infants already possess remarkable discriminatory capabilities: Two-day-old infants can discriminate between stop consonant contrasts (e.g., *ba* vs. *da*) and between following vowel contrasts (e.g., *ba* vs. *bi*; Bertoncini, Bijeljac-Babic, Blumstein, & Mehler, 1987), and by 4 days postnatal age, infants can encode sufficiently detailed information to detect the addition of a new syllable to a set of familiar ones (Jusczyk, Bertoncini, Bijeljac-Babic, Kennedy, & Mehler, 1990). In fact, there are data that suggest that prenatal auditory experience may have an important influence on early speech perception: Three-day-old infants prefer their mothers' voices to those of unfamiliar females (DeCasper & Fifer, 1980; Moon & Fifer, 1990) but have no preference for their fathers' voices (DeCasper & Prescott, 1984); neonates prefer to listen to speech in the parental language, as opposed to speech in a foreign language (Moon, Cooper, & Fifer, 1993); infants at 2 days postnatal age prefer, over a novel story, passages that had been recited by their mothers prenatally (DeCasper & Spence, 1986); and even infants <2 h old, who thus have little postnatal auditory experience, prefer the voices of their mothers to those of five other female voices (Querleu, Renard, Boutteville, & Crepin, 1989).

Since the demonstration by Peiper (1925) that human fetuses respond to external sound, there has been a steady increase in our understanding of fetal auditory perception. Airborne sounds are transmitted to the fetus with relatively little attenuation (Querleu, Renard, Versyp, Paris-Delrue, & Crepin, 1988; D. S. Richards, Frentzeu, Gerhardt, McCann, & Abrams, 1992), and in utero recordings of external voices can be clearly heard, although only approximately 30% of French phonemes can be correctly identified by adult listeners (Querleu et al., 1988). Furthermore, it is now known that the fetal auditory system is sufficiently developed by 35 weeks to respond to a variety of acoustic stimuli: Human fetuses respond

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to pure tones of between 100 and 3000 Hz (Hepper & Shahidullah, 1994) and octave-band noises of between 500 and 5000 Hz (Lecanuet, Granier-Deferre, & Busnel, 1988) and can discriminate between pure tones at 250 and 500 Hz (Shahidullah & Hepper, 1994), between the phonemes /ba/ and /bi/ (Shahidullah & Hepper, 1994), and between male and female voices (Lecanuet, Granier-Deferre, Jacquet, Capponi, & Ledru, 1993).

Attentional processes are especially important in the development of speech perception, not only for distinguishing speech from environmental noise, but also in focusing on relevant acoustic features in the spoken language (Jusczyk et al., 1990). In infants, the major indices of attention have been looking time (see, e.g., Fantz, Fagan, & Miranda, 1975) and heart rate (HR) deceleration (see, e.g., Graham, 1984), but only the latter can be evaluated in human fetuses. The association between HR deceleration and attention can be traced to Sokolov's (1963) description of two generalized reactions to stimulation: a defensive reflex (DR), which serves to protect the individual from intense stimuli by raising sensory thresholds, and an orienting reflex (OR), which acts to prime appropriate receptor systems to the effects of stimulation and, thus, to facilitate information processing. A critical feature of Sokolov's model is that low- and high-intensity stimuli should evoke different responses. This follows from the definition of a DR as a reaction to intense stimulation and implies that, if a directional change in HR occurs, it is the HR response evoked by a low-intensity stimulus that represents an OR (Graham, 1984). There is now a substantial body of data demonstrating that, whereas a DR is associated with an increase in HR, a cardiac deceleratory response is a specific physiological correlate of information processing (Graham, Anthony, & Zeigler, 1983). Furthermore, cognitive resource allocation of stimulus content is thought to be proportional to the magnitude of the HR deceleration (Jennings, 1986; J. E. Richards & Casey, 1992). Human fetuses at ≥36 weeks gestation generally exhibit a sustained monophasic HR deceleration with stimulus onset at low intensity (Groome, Mooney, et al., 1997; Lecanuet, Granier-Deferre, Jacquet, & Busnel, 1992), and the magnitude and time course of this response is very similar to the HR response observed in neonates exposed to low-intensity sounds (Clarkson & Berg, 1983): For both fetuses and neonates, HR decreases rapidly in the first 3–5 sec following stimulus onset, remains at approximately 2–4 beats per minute (bpm) below baseline for the next 2–3 sec, and then gradually returns to prestimulus HR levels. Furthermore, in agreement with Sokolov's model, term fetuses display a change in HR response pattern, from deceleratory to acceleratory, when stimulus intensity is increased (Groome, Mooney, et al., 1997).

Certain kinds of sounds may be especially salient for the human fetus, as compared with other sounds (Jusczyk & Bertoncini, 1988). However, the characteristics of the stimuli that effectively elicit an attentional response in the human fetus are generally unknown. According to Jusczyk (1993), the initial phase of word recognition focuses on the spectral and temporal features of the acoustic signal; and several studies, in neonates and older subjects, have implicated temporal pattern and spectral complexity as critical parameters for eliciting an OR. Clarkson and Berg (1983) found that 2-day-old infants responded to pulsed stimuli with an HR deceleration, whereas continuous stimuli evoked acceleration or no change in HR. Furthermore, the most complex stimulus produced both the largest acceleration for continuous sounds and the largest deceleration for pulsed sounds. Bohlin, Lindhagen, and Hagekull (1981) found that, as compared with continuous stimulation, a pulsed sine wave resulted in a more prolonged HR deceleration in infants 6–8 months of age. A similar trend in the cardiac response was observed at 3–4 months, whereas there was no difference in the HR response between pulsed and continuous stimuli for adult subjects. The data of Miller and Byrne (1983) provide further evidence of differential HR responding in 2-day-old infants. In that study, pulsed stimuli were more effective at eliciting an HR acceleration in sleeping infants than were continuous stimuli. More recently, Byrne, Miller, and Hondas (1994) examined the effect of temporal pattern on the cardiac OR in 3- and 6-month-old infants. Both age groups responded with a larger and more sustained HR deceleration to pulsed than to continuous stimuli.

The present study was undertaken to determine whether temporal pattern and/or spectral complexity were important stimulus parameters for eliciting a cardiac OR in low-risk human fetuses. Inasmuch as it is a basic component of orienting, we expected that the HR deceleratory response in fetuses would depend on stimulus parameters in a manner similar to that observed in neonates. Therefore, we hypothesized that human fetuses would be more attentive to pulsed and complex sounds than to continuous and simple sounds. To test our hypothesis, each of 28 term fetuses was exposed to four sounds formed from the four different combinations of temporal pattern (pulsed, continuous) and spectral complexity (pure tone, phoneme).

METHOD

Subjects

Ninety-four nonsmoking pregnant mothers with no medical or obstetrical complications were recruited from the low-risk obstetrics clinic at the University of South Alabama. Gestation for each mother was between 36 and 40 weeks, based on either a known last menstrual period or a sonogram taken before 20 weeks into the gestation period. This study was approved by the Institutional Review board at the University of South Alabama, and the mothers gave written informed consent prior to participation.

Four (4.3%) fetuses did not respond to any of the four stimuli, and a satisfactory fetal cardiac electrical signal could not be obtained in 36 (38.3%) subjects. In addition, the duration of quiet sleep (QS) for 26 (27.7%) fetuses was too short to complete testing with all four stimuli (8 fetuses received three of the four stimuli, 5 fetuses were stimulated twice, and 5 fetuses received a single stimulus). The subjects who were not included in the data analysis did not differ from the 28 subjects in the study population in racial distribution and infant gender, in gestational age at testing and delivery, in maternal abdominal wall thickness and amniotic fluid volume, and in infant birthweight. Each study subject was in the Medicaid program, 10 (35.7%) of the mothers were white and 18 (64.3%) were black, and 14 (50.0%) of the fetuses were male. The distribution of the sample by race and infant gender was not significant.

The average gestational age of the 28 fetuses at the time of testing was 38.7 ± 1.0 weeks, and the mean interval between fetal testing and delivery was 11.8 ± 7.9 days (range, 1–30 days). Four (14.3%) of the mothers gave birth by caesarean section (1 for nonreassuring fetal status). The average gestational age at delivery was 40.4 ± 1.2 weeks (range, 38.0–42.1 weeks), the average infant birth weight was 3,444 ± 390 g (range, 2,807–4,281 g), no infant was growth-restricted, based on Alabama birth weight standards (Goldenberg et al., 1989), and each infant had a 5-min Apgar score ≥8. Umbilical cord blood gas analyses were not routinely performed on the study subjects. All the infants were initially admitted to the well-baby nursery; 1 infant subsequently developed pneumonia and was treated with intravenous antibiotics. The mean hospital stay of the 28 newborn infants was 1.9 ± 1.8 days (range, 1–9 days). Each infant had a normal neurological profile during a standard physical examination before discharge.

Instrumentation

The fetal cardiac electrical signal was sampled at a rate of 1024 Hz (per channel) over five channels, using Ag-AgCl electrodes attached to the mother's abdomen. A personal computer (486, 33 MHz) was interfaced with an analog-to-digital converter (Metrabyte DAS-20) and connected to five high-performance, low-noise preamplifiers (Grass P511). The data acquisition system was connected via two enhanced bidirectional parallel ports to a second personal computer (Pentium, 60 MHz). The second computer was used to deliver the acoustic signal (Soundblaster, 16 board, Creative Labs) and was synchronized with the first computer by integrating the parallel communications network directly into the acquisition software.

Stimuli

The temporal pattern was either pulsed or continuous, and the sounds were either simple (sine wave) or complex (/â/). Four stimuli were formed from the four different combinations of temporal pattern and complexity (continuous /â/, pulsed /â/, continuous sine wave, pulsed sine wave).

A sine wave was computer generated at a frequency of 1000 Hz and stored as a digital file. The /â/ phoneme was spoken in a female voice and was maintained for 7.3 sec. The spectrogram of the /â/ phoneme was reviewed, and a 500-msec segment was removed from the most homogenous region of the 7.3-sec sound; the removed segment contained equivalent full-scale amplitudes throughout its entire duration. The frequency spectrum of the 500-msec /â/ consisted of a small peak in amplitude at 190 Hz and three large peaks centered around 1000 Hz; the first three formant frequencies were 711, 947, and 2821 Hz.

The continuous sine wave consisted of a 30-sec segment of the stored digital file. The continuous /â/ was created by first replicating the 500-msec segment and then splicing the replicated segments at exact peak amplitudes, so that there were no breaks or inhomogeneities in the sound. Pulsed stimuli were generated by alternating 500-msec sounds with 500-msec quiet periods.

Stimulus onset was linear for each sound, with a rise time of 500 msec to full amplitude; for pulsed stimuli, all rise times after the first pulse were fixed at 10 msec to full amplitude. The fall time for the continuous /â/ and the continuous sine wave was 10 msec, and the fall time was 10 msec for each 500-msec sound in the two pulsed stimuli. Each stimulus lasted 30 sec.

The stimuli were delivered over a 16.5 × 21.6 cm Super Powerhorn speaker (Realistic) suspended from the ceiling on a moving track and positioned 10 cm above the maternal abdomen during the study session. Prior to the mother's arrival at the fetal testing unit, a 35-W amplifier (Realistic MPA-45) was adjusted to provide an average intensity of 83 dB (A-scale) at a distance of 10 cm (Realistic 33-2055 sound pressure meter). Each mother wore earphones and listened to classical music during fetal testing; 8 (28.6%) mothers heard at least one of the four sounds, but only 5 (17.9%) could describe the sound.

Procedure

The mothers were instructed to fast after midnight on the day preceding a scheduled study session and were given a standard meal (280 cal) on arrival at the fetal testing unit. After they completed the meal, amniotic fluid volume was measured with ultrasound (Phelan, Smith, Broussard, & Small, 1987), and fetal HR was monitored for 60 min, using a Doppler-based cardiotocograph (Hewlett-Packard Model M1351 A, series 50). The mother was then asked to ambulate and use the restroom as needed. No study was begun after 1100 h.

All the examinations were performed in a quiet room (background sound pressure level, <50 dB), with the mother resting comfortably in a semirecumbent position. To facilitate on-line assignment of behavioral states, fetal HR was monitored during the prestimulus period, using the Doppler cardiotocograph, and fetal eye movements were assessed by positioning a 5-MHz convex linear-array ultrasound transducer (Aloka 620, Corometrics) to obtain a parasagittal view of the fetal face. The ultrasound transducer was positioned in such a way as to videotape movements of the fetal thorax during the prestimulus and stimulation periods. At the time of video playback, the fetal respiratory pattern was classified as continuous (defined as having no more than an approximately 6-sec pause between breaths; Patrick, Campbell, Carmichael, Natale, & Richardson, 1980), nonbreathing (defined as the complete absence of breathing activity), or intermittent (in which the pattern was neither continuous nor nonbreathing).

The mother's abdomen, right forearm, and left calf were thoroughly cleansed with ethyl alcohol at the beginning of each study session. A commercially available preparation (Baxter electrode) was then applied to the maternal skin, and Ag-AgCl electrodes were attached with conducting gel patches to the mother's right arm and left leg and at four locations across the maternal abdomen, as determined by the position of the fetal heart. All five channels were visualized simultaneously with the aid of an interactive graphical display. Final gain and filter settings and electrode placement were determined by optimizing fetal R-wave recognition in at least two channels.

All the stimuli were delivered while the fetus was in QS, which was assumed (Groome, Swiber, Atterbury, Bentz, & Holland, 1997) to be equivalent to fetal behavioral state 1F, as originally defined by Nijhuis, Prechtl, Martin, and Bots (1982): no eye movement, a stable baseline HR pattern with little variability, and infrequent general body movement. In cases in which the fetal eyes could not be visualized, behavioral state was assigned on the basis of HR pattern and body movement. The order of stimulus presentation was determined by randomly assigning subjects to each row of a 4 × 4 Latin square, and there was at least a 2-min period between successive stimuli. Each fetus remained in state 1F for 3–5 min before a stimulus trial was initiated. Data were collected in 90-sec blocks, consisting of a 30-sec prestimulus period, a 30-sec stimulation period, and a 30-sec poststimulus period. For each stimulus trial, fetal eye movements were assessed with ultrasound at the beginning of the 30-sec prestimulus period and at the end of the 30-sec stimulation period. A state change was assumed to have occurred if there was fetal eye movement or if the HR was more reactive (i.e., pattern B, as defined by Nijhuis et al., 1982) after stimulation. Trials confounded by a state change and/or fetal movement in the 30-sec prestimulus period were not analyzed but were repeated in the next occurring QS period. The study session was completed if the fetus had remained in QS for all four stimuli and if there had been no fetal movement during the 30-sec prestimulus period. Each fetus was examined once.

Data Reduction

The raw signal recorded from the mother's abdomen contained both the fetal R-waves and the maternal cardiac electrical signal. Each 90-sec block was scanned on the computer screen to identify the maternal R-waves. The location of each maternal R-wave was visually approximated, using an interactive graphical interface, and the precise location of the R-wave was determined by a digital search routine that converged on either the maximum (upright R-wave) or minimum (inverted R-wave) electrical amplitude. Once a maternal R-wave was located, a 350-msec segment on each side of the R-wave was used to model the maternal cardiac complex (MCC), and a maternal cardiac template was constructed by averaging the index MCC and the four MCCs immediately preceding and following the index MCC. This template was subtracted from the raw signal, leaving a residual signal that contained only fetal R-waves. The location of each fetal R-wave was determined by using the same interactive graphical interface and the same digital search routine. All calculations were performed using the fetal R-wave data.

The technique for artifact detection was based on the distribution characteristics of successive heart period differences for individual subjects, as described by Bernston, Quigley, Jang, and Boysen (1990). The most conservative estimate for artifact detection is the maximum expected difference (MED) for nonartifact beats, which can be calculated by multiplying the interquartile range in heart period differences by 1.66 (Berntson et al., 1990). For each 90-sec block, successive heart period differences that were greater than the MED were identified as suspicious. Potential artifacts were assumed to represent a physiological change in HR if the heart period difference did not appear to deviate from the ongoing pattern of variation according to the criteria of Schechtman, Kluge, and Harper (1988). Heart period differences that were identified as artifacts were replaced either with the sum of two or more small intervals or with the average of two or more intervals (Schechtman et al., 1988).

Data Analysis

Each 90-sec block was converted to equally spaced data by calculating the weighted HR for consecutive 100-msec windows. Mean HR at each 0.5 sec was calculated by averaging the HR at the index time and the five weighted HRs immediately preceding and following the index value. The HR response was analyzed for the first 12 sec following stimulus onset. Repeated measures analyses were performed with the BMDP-2V (1992) analysis of covariance (ANCOVA) programs. Between-subjects factors were race and sex of infant; within-subjects factors were HR over time, in bpm; and covariates were HRs (in bpm) in the 1-sec period immediately preceding stimulus onset, order of stimuli, and fetal breathing movements (present or absent). Within-subjects effects were tested by calculating linear, quadratic, and cubic orthogonal polynomial trends.

In trend analyses, it is generally assumed that single degree of freedom contrasts take precedence over other statistics. Components in a polynomial trend analysis (e.g., linear, quadratic, etc.) test changes across the repeated measures (seconds in this report) and also test the interaction of between- and within-group factors. Polynomial analyses do not require compound symmetry—that is, the use of the Greenhouse–Geisser or other less conservative adjustments, when data fail to satisfy the sphericity requirement (BMDP-2V, 1992). The single degree of freedom contrasts in a repeated measures experiment can be trusted when all else fails (SPSS, 1996). We had anticipated quadratic curves on the basis of the results of a previous study (Groome, Mooney, et al., 1997); hence, statistics testing quadratic trends may be regarded as planned comparisons. Therefore, we hypothesized that each stimulus would elicit a quadratic HR response curve, and on the basis of the results of other studies (Bohlin et al., 1981; Byrne et al., 1994; Clarkson & Berg, 1983), we also hypothesized that pulsed stimuli would produce a greater average HR deceleration than would continuous stimuli and that the phoneme /â/ would result in larger HR decelerations than would the sine wave. Tests of specific hypotheses accepted the .05 level as statistically significant.

RESULTS

The prestimulus HR characteristics are summarized in Table 1 for each stimulus type. There was no difference between the four stimulus groups in either the mean or the standard deviation in prestimulus HR, indicating that there was no measurable difference between trials in prestimulus behavioral state. Furthermore, for all stimulus groups, there was no difference in average HR between the 1-sec period preceding stimulation and the 30-sec baseline period.

The average onset response curves for the four stimuli are shown in Figure 1 for successive 0.5-sec intervals. Inspection of the curves showed that, on average, the two pulsed sounds elicited an HR deceleration of approximately 2 bpm, whereas the HR responses to the two continuous sounds were inconsistent and of lesser magnitude than the HR responses to the pulsed sounds. Race and infant gender were between-subjects factors in the ANCOVA, and the within-subjects factors were temporal pattern (continuous or pulsed), stimulus complexity (/â/ or sine wave), and consecutive HRs. Three covariates were used in the first analysis (1-sec prestimulus HR, order of stimulus presentation, and breathing movements [present/

Table 1
Prestimulus Heart Rate Characteristics

	Stimulus Group (*n* = 28)							
	Sine–c		Sine–p		/â/–c		/â/–p	
Prestimulus Period	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
30-sec								
Mean (bpm)	131.10	7.20	130.50	6.80	130.20	6.40	131.10	5.80
Standard deviation (bpm)	1.85	1.36	1.62	0.59	1.79	0.78	1.65	0.64
1-sec								
Mean (bpm)	130.70	8.20	131.10	6.70	130.00	6.10	130.90	6.30

Note—c, continuous; p, pulsed; bpm, beats per minute.

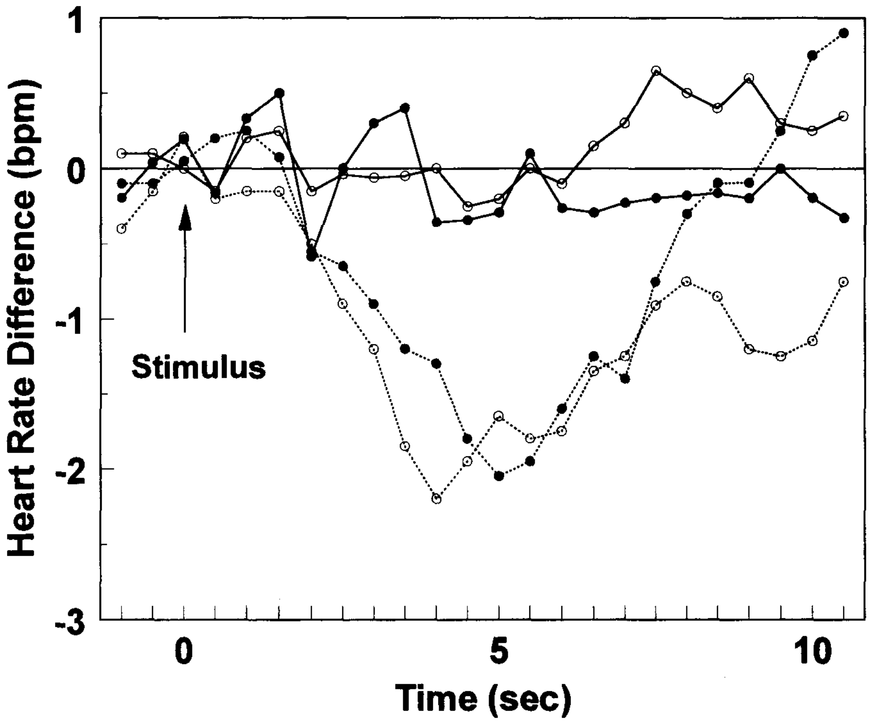

Figure 1. Onset response to stimulation with the phoneme /ā/ and the 1000-Hz sine wave in a continuous and pulsed temporal pattern. Responses are plotted in 0.5-sec increments after stimulus onset and represent the change in heart rate from the mean heart rate in the 1-sec period immediately preceding stimulation. Filled circle, phoneme; open circle, sine wave; solid line, continuous; broken line, pulsed.

absent]), and these values changed with stimulus trial. Between-subjects variables were not statistically significant in this analysis. However, prestimulus HR was a significant covariate in the between-group analysis, [$F(1,23) = 469, p < .001$] and in the analysis of spectral complexity [$F(1,23) = 72, p < .001$] and temporal pattern [$F(1,23) = 111, p < .001$]. HR change over time was significant [$F(23,551) = 6.37, p < .001$], and there was also a significant interaction between time and temporal pattern in this omnibus analysis [$F(23,551) = 7.45, p < .001$].

Next, variables found to be nonsignificant in the first analysis were eliminated, retaining the 2 × 2 complexity-by-temporal-pattern format in the within-subjects analysis; 1-sec mean prestimulus HR was the only covariate. As in the omnibus analysis, HR over time for the stimuli combined was significant [$F(23,621) = 7.97, p < .001$]; this time trend was also significant by the conservative Greenhouse–Geisser adjustment ($p < .001$). The interaction of temporal pattern and time, as before, was also significant [$F(23,621) = 2.54, p < .001$ ($p < .049$ by Greenhouse–Geisser)]. The effect of stimulus complexity was not significant in this or the previous analysis. Single degree of freedom contrasts based on means of the four stimuli indicated that HR over seconds was significant [$F(1,27) = 6.05, p < .021$, for linear trends; $F(1,27) = 13.77, p < .001$, for quadratic trends; and $F(1,27) = 8.10, p < .009$, for cubic trends]. To follow up on these composite results, a repeated measures ANCOVA was computed for each stimulus separately, with prestimulus HR as a covariate. Only the pulsed stimuli showed significant quadratic effects: [$F(1,27) = 9.29, p < .005$, for the pure tone, and $F(1,27) = 16.15, p < .001$, for the phoneme]. Linear and cubic components were also significant for the pulsed /ā/ [linear $F(1,27) = 9.91, p < .005$, and cubic $F(1,27) = 5.32, p < .03$].

Finally, four ANCOVA analyses were performed to compare the consecutive means over time for pulsed /ā/ versus continuous /ā/, pulsed sine wave versus continuous sine wave, combined pulsed sounds versus combined continuous sounds, and combined /ā/ versus combined sine wave. Only the significance of the interactions are presented, since we were primarily interested in differences among stimuli across time. The interaction between the pulsed /ā/ and the continuous /ā/ was significant [$F(1,27) = 6.91, p < .015$], even though there was no difference in the mean HR responses between these two sounds. The comparable statistics for the other contrasts were $F(1,27) = 3.45, p < .07$, for the pulsed sine wave versus the continuous sine wave, and $F(1,27) = 6.05, p < .016$, for the combined pulsed versus the combined continuous stimuli. The interaction of the combined /ā/ versus the combined sine wave was not significant.

DISCUSSION

Observations made in the postnatal period, demonstrating an effect of prenatal auditory experience on infant speech perception (DeCasper & Fifer, 1980; DeCasper & Spence, 1986; Moon et al., 1993; Querleu et al., 1989), suggest that the perinatal infant is capable of encoding detailed auditory information before birth. Attentional processes play a major role in the kind of auditory information that is encoded (Jusczyk et al., 1990), and the HR deceleratory response, as a basic component of the OR, is a physiological measure of information processing of stimulus content. In the present study, we sought to identify the characteristics of airborne sounds that were most effective at eliciting a cardiac OR in human fetuses. On the basis of an analysis of the magnitude and time course of the HR deceleratory response, we found that attention was more strongly directed toward the temporal feature of the signal than toward its spectral component. For the pure tone and the phoneme used in this study, our results indicate that early development of speech perception may be particularly influenced by temporal features of the spoken language heard prenatally. However, we also recognize that the use of other stimuli, especially sounds with larger spectral differences, may demonstrate a greater role for spectral complexity in eliciting a cardiac OR in human fetuses.

Graham (1979) distinguished between signal detection and information processing by noting that the former occurs in response to stimulus transients and the latter occurs during sustained stimulation. Transient and sustained processing systems are assumed to operate in parallel, over different neural pathways, and to give rise to the entire orienting sequence (Berg & Berg, 1987; Graham, 1984). Presumably, rapid stimulus change, transmitted by fast-conducting neurons, triggers a transient detecting reflex (TDR); this, in turn, activates information processing by longer latency pathways, resulting in an OR. However, the ability to process a rapid change in stimulus intensity may not be fully developed in newborn infants (Graham et al., 1983), suggesting that fetuses may not respond to stimulus onset if the rise time is too fast. Therefore, to increase the likelihood that an HR response would occur, we fixed the rise time for stimulus onset at 500 msec for both the continuous and the pulsed sounds. However, since transient processing is weaker in infants than in adults (Graham et al., 1983), it is unlikely that a single TDR elicited by a single transient (i.e., continuous stimulation) will trigger an OR (Berg & Berg, 1987). On the other hand, stimulus traces persist and summate over longer intervals in infants than in the adult. As a result, repetition of a low-intensity sound (i.e., pulsed stimulation) while some energy remains from an earlier presentation may increase the probability of eliciting an OR, provided transients can summate to activate the longer latency pathway (Berg & Berg, 1987). Our finding, that pulsed sounds elicited an HR deceleration but continuous sounds did not, are consistent with postnatal studies (Bohlin et al., 1981; Byrne et al., 1994; Clarkson & Berg, 1983) and suggests that processing of temporal pattern undergoes relatively little change from fetal life to the neonatal period to infancy.

Whereas neonates seem to exhibit a greater HR response to complex sounds than to simple sounds (Clarkson & Berg, 1983), we did not find this to be true for fetuses: Our analyses, comparing the HR response to a phoneme with that to a pure tone, indicated that the magnitude of the cardiac OR was relatively unaffected by spectral complexity (although the pulsed /â/ resulted in a more complex HR response than did the pulsed sine wave, as judged by the number and magnitude of the polynomial components). However, several factors could affect the interpretation of our findings. Compared with airborne sounds at frequencies ≥500 Hz, low-frequency sounds penetrate the uterus more effectively (Querleu et al., 1988) and are transmitted to the fetal inner ear at a higher intensity (Gerhardt et al., 1992), and sound pressure levels may actually be enhanced at frequencies below 250 Hz (Gerhardt, Abrams, & Oliver, 1990). We intentionally chose stimuli with frequencies ≥500 Hz: Compared with lower frequency sounds, these sounds are less likely to be amplified (Gerhardt et al., 1990) and thus are also less likely to evoke a startle reflex. The frequency of the sine wave was set at 1000 Hz so that differences in the HR response between the /â/ and the sine wave could not be attributed solely to a difference between the two stimuli in average sound frequency. In addition, short fall times (e.g., 10 msec) may introduce considerable spectral splatter, which may further reduce spectral differences between the pulsed sine wave and the pulsed /â/. Therefore, although the phoneme was spectrally more complex than the pure tone, spectral differences between the /â/ and the sine wave may not have been sufficient to effect a difference between the two stimuli in the magnitude of the HR response.

Early studies in neonates have shown that the cardiac OR is most easily elicited during periods of quiet alert (Graham et al., 1983), whereas, and in contrast to human fetuses, stimulation during sleep results in either an acceleratory response (Clifton & Nelson, 1976) or a brief, 1-sec HR deceleration followed by an acceleration (Schachter et al., 1971). Although this may represent a true developmental change in information-processing capabilities, we also note that sleep–wake states are defined differently in fetuses and neonates. For practical reasons, fetal sleep–wake states are usually defined in terms of spontaneous behaviors that can be assessed with real-time sonography (e.g., eye and body movements) and physiological variables that can be measured noninvasively (e.g., HR pattern). The two most common fetal behavioral states, states 1F and 2F, seem to be closely related to the neonatal states of QS and active sleep (AS), respectively (Groome, Swiber, et al., 1997). However, on the basis of the operational definitions of Nijhuis et al.

(1982), human fetuses spend very little time (Groome & Watson, 1992), if any (Pillai & James, 1990), in a state of quiet alert. In support of this (even though it must be recognized that there are large interspecies differences), arousal states have not been observed in the sheep fetus under normal conditions (Hasan & Rigaux, 1992; Rigatto, Moore, & Cates, 1986). Therefore, and in contrast to the newborn infant, almost every normal human fetus will cycle between QS and AS, but the majority of fetuses only infrequently enter a wake state, as defined by Nijhuis et al. Our findings indicate that fetuses exhibit a cardiac OR in a behavioral state that is very similar to the neonatal state of QS, but we acknowledge that differences in state definitions may confound the interpretation of these data.

In summary, we found that processing of the temporal feature of an auditory stimulus in term fetuses, as reflected by an HR deceleratory response, did not differ qualitatively from that of neonates and older subjects: Consistent with postnatal studies (Bohlin et al., 1981; Byrne et al., 1994; Clarkson & Berg, 1983), fetuses were more likely to exhibit an HR deceleration in response to pulsed sounds than in response to continuous sounds. On–off stimulation conveys more information than continuous stimulation; and since greater orienting occurs with more information (Sokolov, 1963), the finding that pulsed stimuli elicited a greater HR deceleration than did continuous stimuli is consistent with Sokolov's conceptualization of the OR (Clarkson & Berg, 1983). However, pulsed sounds also contain more transients than do continuous sounds of the same duration, so that it is not possible to attribute the difference in the HR response solely to a difference in the information content of the two stimuli: Pulsed stimuli, with multiple transients, may trigger a TDR that, in turn, gives rise to an OR (Berg & Berg, 1987). Delineating the characteristics of the stimuli that elicit a cardiac OR in fetuses will not only help identify mechanisms that trigger orienting but will also provide insights into how infants process auditory information at a more general level.

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