Developmental Science 2:2 (1999), pp 206–218

PAPER

Emerging self-exploration by 2-month-old infants

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Abstract

Two-month-olds and newborns were tested in a situation where they had the opportunity to experience different auditory consequences of their own oral activity on a dummy pacifier. Modulation of oral activity was scored and analyzed relative to two types of contingent auditory feedback, either analog or non-analog to the effort exerted by the infant on the pacifier. The dummy pacifier was connected to an air pressure transducer for recording of oral action. In two different experimental conditions, each time the infant sucked above a certain pressure threshold they heard a perfectly contingent sound of varying pitch. In one condition, the pitch variation was analog to the pressure applied by the infant on the pacifier (analog condition). In another, the pitch variation was random (non-analog condition). As rationale, a differential modulation of oral activity in these two conditions was construed as indexing some voluntary control and the sense of a causal link between sucking and its auditory consequences, beyond mere temporal contingency detection and response–stimulus association. Results indicated that 2-month-olds showed clear signs of modulation of their oral activity on the pacifier as a function of analog versus non-analog condition. In contrast, newborns did not show any signs of such modulation either between experimental conditions (analog versus non-analog contingent sounds) or between baseline (no contingent sounds condition) and experimental conditions. These observations are interpreted as evidence of self-exploration and the emergence of a sense of self-agency by 2 months of age.

Much progress in infancy research is based on the behavioral plasticity of young infants. Instrumental learning and conjugate reinforcement of head turning or leg kicking have been used extensively to document early perceptual and memory capacities (Papousek, 1959; Watson & Ramey, 1972; Kuhl, 1985; Juczyck, 1985; Rovee-Collier, 1987). Major findings on infant perception and action originated from experimental paradigms that capitalized on the plasticity of newborns' sucking behavior. In a seminal study, Siqueland and DeLucia (1969) demonstrated that 4- to 12-month-old infants tended to suck significantly more on a dummy nipple when it was associated with the contingent increase of a light source illuminating a visual display. Within less than 3 minutes of such response–stimulus conjugation, Siqueland and DeLucia showed that infants increased markedly the frequency of their sucking. In controls, they reported no evidence of learning for those infants whose sucking had either the reverse effect of reducing the intensity of the light source or no contingent visual consequences. Within a habituation paradigm, conjugate reinforcement of high-amplitude sucking has been used extensively to investigate the early development of speech sounds discrimination and categorization (Eimas, Siqueland, Jusczyk & Vigorito, 1971; Eimas, 1985). In these studies, infants are reported to learn quickly that sucking above a predetermined amplitude threshold is accompanied by a contingent sound. Typically, the sucking response rate of the infant increases during the first 3 minutes of reinforcement and then decreases as a sign of habituation. When a certain habituation criterion is reached, infants are then presented with a novel sound as reinforcer. Increase in sucking rate following the auditory consequence change is used as an index of dishabituation and hence discrimination between habituation and post-habituation sounds (Jusczyk, 1985).

Aside from being useful as a technique to unveil infants' learning, memory and perceptual capacities, instrumental learning via sucking reveals that infants from birth are actively engaged in exploring the

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perceptual consequences of their own actions and hence their own agency in the environment. One possibility, however, is that instrumental learning via sucking demonstrates nothing more than surface flexibility in the use of a high functioning action system at birth (sucking), outside of its primary function (i.e. feeding or the extraction of food from a nipple). Following this lean interpretation, such flexibility would rest on strict associations between motor responses and new perceptual consequences that reinforce these responses. The essence of such flexibility would be the temporal contiguity between response (R, i.e. sucking) and stimulus (S, i.e. perceptual consequence in the environment). Alternatively, instrumental learning might be the first signs of a developing ability to differentiate between means (e.g. sucking) and ends (new, interesting perceptual consequences).

The inclination to explore the perceptual consequences of self-produced action is a trademark of infancy. An important question is what infants learn from exploring these consequences. Piaget (1952), and Baldwin (1906) before him, noted that by the second month infants engage in systematic, playful repetitions of action schemes, first on their own body (primary circular reactions) and eventually on external objects (secondary circular and tertiary circular reactions). According to the constructionist/structuralist view of Piaget, circular reactions index the development of novel sensorimotor schemes based on systematic exploration and active modulation of behavior by the infant. From a functional perspective, the propensity for repetitive action schemes might favor the discovery of one's own effectivity and vitality. Repeating actions such as bringing the hand to the mouth (Butterworth & Hopkins, 1988; Rochat, Blass & Hoffmeyer, 1988), thumb sucking, or the kicking of a mobile enable young infants to calibrate the effectivity of their own actions, as well as to specify their own force and vitality (Rochat, 1995). In this view, the inclination to explore systematically the perceptual consequences of repeated, self-produced action is a primary source of self-knowledge, in particular of the process underlying the development of a sense of self as agent, differentiated from other objects in the environment (i.e. the *ecological self*, Neisser, 1991; Rochat, 1997; see also Butterworth, 1992).

Few studies suggested that by 2 months infants appear to pay particular attention to the effect of their own action not only on their own body but on objects in the environment. Lewis, Sullivan and Brooks-Gunn (1985) attached to one wrist of 2-month-olds a cord connected to a music box that triggered interesting sounds and sights when pulled. Compared to a baseline period when the cord was not attached to the box, infants learned within minutes to make the appropriate arm action to trigger the music box. The frequency of arm pulls was reported to increase significantly and infants displayed positive affect via smiling. Interestingly, during a second (extinction) baseline, infants were reported to continue to pull at an even higher rate in an apparent attempt to obtain the reinforcing consequence. Congruent with their apparent experience of frustrated expectations, infants displayed a marked reduction in smiling and a significant increase in anger expression during this extinction phase. Lewis *et al.* interpreted these observations as suggesting that infants from 2 months explored themselves as agents of action and transformation in the environment, rapidly learning new ways to impact on objects. They also pointed to the fact that aside from perceiving and acting adaptively in a new environmental situation (i.e. learning to move their arm), young infants developed expectations about what should happen next in a situation where they were agent of interesting perceptual events. Accordingly, the emotional expression of smiling and anger reported by Lewis *et al.* would index young infants' sense of self-agency and the anticipation of particular consequences of self-produced action. Evidence of a sense of self-agency by 2-month-olds might call for a new conceptualization of the developmental origins of intentional action (Lewis, 1991), means–end differentiation (Piaget, 1954; Frye, 1991) and self-knowledge (Gibson, 1995). However, such evidence needs further support. In relation to Lewis *et al.*'s observations, it is still possible to argue that the differential emotional expression of infants during the learning and extinction phases of the experiment might be due to a mere change in overall arousal associated with either the contingent perceptual event (music box 'on') or its absence. Following such interpretation, these observations would not entail any precocious sense of self-agency. The present experiment has been conceived in part to provide some control over this possible interpretation. Furthermore, the kind of response used by Lewis *et al.* (arm pull) does not allow the origins of such instrumental learning and exploration to be investigated in infants younger than 2 months who might lack sufficient upper-limb control to learn and explore their own agency (but see Van der Meer & Van der Weel, 1995).

Instrumental learning of sucking behavior has been used successfully in research on speech sound and voice perception in newborns and infants younger than 2 months (Eimas *et al.*, 1971; DeCasper & Fifer, 1980). In DeCasper and Fifer (1980), newborns were reported sucking on a nonnutritive nipple in different ways in order to produce either their mother's voice or the voice of another female stranger. Within minutes, they learned to modulate the duration of intervals between sucking bursts to hear their mother's voice preferentially. In their pioneer work, Kalnins and Bruner (1973) studied instrumental learning of sucking by young infants with the idea of exploring the developmental origins of voluntary control of action. Kalnins and Bruner considered whether young 5- to 12-week-old infants would display some voluntary control of action. They proposed five distinct features of voluntary action control. In all, these features would distinguish voluntary action from action that might be reduced to mere automatic R–S associations or behavior under stimulus control. The proposed features were (1) the ability to anticipate an outcome; (2) the capacity to choose means to achieve a goal; (3) the ability to modulate action leading to a goal; (4) the ability to bring action to a close once a desired state is attained; and (5) the ability to substitute means to achieve a goal. To test such features in young infants, Kalnins and Bruner presented young infants with a silent film whose optical clarity (focus) was contingent on their sucking on a nonnutritive pacifier. Half of the infants had to suck on the pacifier in order to bring the film into focus and the other half had to inhibit sucking to achieve the same goal. Infants were reported to learn very quickly to suck in order to achieve the goal of bringing the film into focus. However, Kalnins and Bruner found that such learning was optimum when infants had to suck for a clear image compared with when they had to pause. They conclude that young infants are better at using an active rather than an inhibitory mode as a means to achieve instrumental control.

Although the study of Kalnins and Bruner (1973) and the infant-controlled sucking technique successfully used by DeCasper and Fifer (1980) with newborns might suggest early signs of problem-solving activity and voluntary control beyond mere R–S associations, they do not provide information regarding the developmental course of such abilities. Furthermore, because infants' instrumental learning was based on the production of sucking frequency above a predetermined threshold of pressure on the pacifier (on–off principle), these studies did not allow documentation of the extent to which infants engage in *exploring their own effectivities* while learning to act on the pacifier towards the goal of producing certain perceptual outcomes. Aside from studying infants' learning to suck in order to obtain certain auditory outcomes, the present research was designed to capture when young infants start to explore the relation between their own activity (sucking) and various effects that are equally contingent but differentially congruent.

Rationale

We studied infants in a situation where they had the opportunity to learn about different auditory consequences of their own sucking behavior. The question was not whether young infants could learn to suck in order to produce a sound, a well-documented fact (see above), but whether this ability might entail more than the mere detection of a temporal contiguity between oral response and stimulus. In particular, beyond merely detecting the temporal co-occurrence of what they do (i.e. sucking) and what they hear, the aim of the research was to investigate when infants start to demonstrate some signs of a systematic exploration of their own agency in producing sounds contingent to their sucking. The rationale of the research is based on what we view as a subtle but fundamental difference between contingency detection and the detection of a causal link between an action and its perceptual consequences. Contingency detection by young infants demonstrated in previous studies does not necessarily entail any differentiation between the instrumental act performed (sucking) and its consequences (the production of particular auditory effects). So far, the operant learning demonstrated by young infants can still be interpreted as stimulus controlled (mere R–S association), not entailing any of the features of voluntary control proposed by Kalnins and Bruner (1973). One way to clarify this issue and demonstrate that voluntary control is involved in early operant learning is to provide some evidence of problem-solving activity on the part of the infant, not simply progressive shaping of their response. Such problem-solving activity would be evident if infants demonstrate some systematic modulation of their own action to obtain different effects that are equally contingent. In other words, evidence of a sense of self-agency would be indexed by infants modulating their sucking activity as a function of the relative analogy (spatial congruence) between the action and its perceptual consequences, considering that they are both equally contingent. It is important to distinguish between two levels of perceptual discrimination that might underlie instrumental learning. Let us take the example of a mobile attached to one of the infant's legs (Rovee-Collier, 1987). Following kicking and its conjugate reinforcement, infants might gather two fundamentally different kinds of information. They might detect that there is a coincidence between propioceptive and visual feedback. In this case, infants might get aroused by such coincidence and hence reinforced to kick more by strict R–S association. Alternatively, in addition to detecting the temporal contingency between kicking and the mobile's movements, they might also detect a certain analogy or spatial congruence between leg movements and the way the mobile moves. We propose that such sensitivity cannot be based on blind R–S association, but rather on the systematic probing and exploration of the particular relation between self-produced action and its contingent consequences. The demonstration of such sensitivity by young infants would strongly suggest that some voluntary control underlies instrumental learning. By analogy, there is a fundamental difference between learning to blow into a horn above a certain threshold to produce a sound (any sound) and learning that the way one blows into a horn will systematically change the sound it produces. The former corresponds to mere contingency learning (i.e. 'honking'), the latter to the exploration of the self as agent (i.e. learning to play music).

With this research, we attempted to capture whether 2-month-old infants and possibly newborns might demonstrate some modulation of their oral activity as a function of auditory consequences that are contingent but correspond more or less to the oral activity they exert on a dummy pacifier. In particular, we asked whether 2-month-old infants and eventually newborns would demonstrate systematic modulation of their instrumental sucking response depending on contingent auditory effects that are either *analog* or *non-analog*. Infants were presented with a pacifier introduced in their mouth for sucking. The pacifier was connected to an air pressure transducer and, in two different experimental conditions, when the infants sucked above a certain pressure threshold they heard a perfectly contingent succession of discrete sounds of varying pitch. In one condition, the pitch variation was analog to the pressure applied by the infant on the pacifier (*analog condition*). In another condition, the pitch variation was random relative to the pattern of pressure applied on the pacifer (*non-analog condition)*. We considered that a differential modulation of oral activity in these two conditions would index some voluntary control and the sense of a causal link between sucking and its auditory consequences, beyond mere temporal contingency detection and R–S association. We expected to observe such modulation in 2-month-olds but not in neonates, providing further evidence of an emerging sense of self-agency by at least 2 months of age.

Method

Participants

A total of 32 infants were tested: 18 2-month-olds (11 boys, seven girls) and 14 newborns (seven boys, seven girls). Newborns were tested at Atlanta Northside maternity hospital where they were born. All newborns had at least 36 weeks of gestation and had a 1 and 5 minute Apgar score of 7 or higher. The mean age of the newborn infants at the time of testing was 25.6 hours (range 23–29.5 hours, SD = 2.25). They were tested in between feedings, taken from their mother's room into an adjacent testing room. The testing room was quiet. Three additional newborns were tested but were excluded from the study, two because they fell asleep during test and one because of fussing. Newborns were in an active state during testing to the extent that they were included in the study only if they were exerting oral pressures on the pacifier above threshold in each of the test blocks (see procedure below). Two-month-olds were recruited from a large pool of potential participants all living in the Greater Atlanta area. They were brought by their caretaker to the Emory Infant Laboratory for testing in a quiet room dedicated to the study. The mean age of 2-month-olds was 2 months 12 days (range 1 month 27 days to 2 months 27 days, SD = 9.8 days). Five additional 2-month-olds were tested but excluded from the final sample, three because of fussiness, one because of experimental error and one because he refused the pacifier. All infants were tested on average 2 hours after last feeding. Two-month-olds were all full-term healthy infants with no diagnosed hearing problems and were all in an alert active state during all phases of testing.

Technique and equipment

Newborns were tested while lying supine in their bassinet and 2-month-olds were seated in a 60° reclined infant seat. Two speakers (Optimus Model XTS25) were placed above the infant's head and parallel to each of the infant's ears at a distance of 10 inches. With newborns the speakers were placed inside the bassinet and for the older group they were placed on each side of the infant seat.

A camera was positioned in front of the infants (approximately 6 feet away) and provided a close-up view of their face. This image was fed into a video image mixer (Pelco BUSS200DT) to be superimposed and synchronized with the computer display of the on-line recording of the infant's sucking using an AverdiaMedia television converter. As illustrated in Figure 1, the resulting image used for coding was the synchronized frontal view of the infant with an on-line graphic representation of the pressure applied on the pacifier by the infant, as recorded by the computer (Power Macintosh 7100/80 with an analog to digital board, using Lab View Inc. program software). A program was

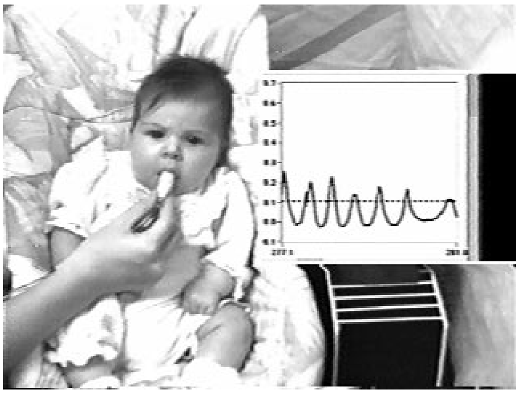

Figure 1 *Video image used for coding, consisting of a synchronized and mixed frontal view of the infant with the on-line graphic representation of the pressure (psi) applied on the pacifier by the infant, as recorded by the computer. The horizontal dotted line represents the pressure threshold for auditory feedback in the experimental conditions (contingent analog or contingent non-analog).*

written specifically for the purpose of this research, using Lab View, to create two experimental conditions of contingent auditory reinforcement upon sucking (see below).

Infant sucking was recorded via a Playtex Soft Comfort pacifier covered with a sterile rubber finger-coat. The pacifier was connected via soft rubber tubing to an air pressure transducer (Omega PX139–001d4V) which outputted a voltage in the range. 0.5–4.5 V for a pressure range of 0 to 1 pound per square inch of air (psi). The transducer transformed positive pressures applied on the pacifier by the infant into an analog electrical signal digitized by the computer for recording and on-line graphing, as shown in Figure 1. Furthermore, the computer was programmed to output various contingent auditory signals that corresponded in various ways to the pressure applied on the pacifier. These auditory signals were amplified and fed back to the infant via the speakers depending on two different experimental conditions, described next.

In a first experimental condition (analog condition), each time infants sucked above a minimum pressure threshold of 0.1 psi as recorded by the computer, they heard a perfectly contingent (zero delay) continuous sound with frequencies varying on a continuum or crescendo–decrescendo pattern (frequency glide) that was *commensurate* with the amount of pressure applied on the pacifier. The minimum pressure threshold of 0.1 psi was chosen to minimize the pressure effort on the pacifier required to obtain auditory feedback. Even infants with weak oral responses had an opportunity to learn and be reinforced with auditory consequences. Preliminary tests based on five successive 2 s continuous and regular mechanical pressures and releases on the pacifier (0 to 0.6 psi maximum) indicated that the average sound frequency produced was 183 Hz (SD 40.8) with an intensity of 63–68 dB.

In a second condition (non-analog condition), each pressure above threshold produced a 550 ms continuous trill of sounds (11 sounds of 50 ms each) varying randomly in frequency between 0 and 400 Hz. These sounds were temporally contingent to each oral pressure on the pacifier but their abrupt frequency change was not commensurate to the amplitude change of the pressure. Each time infants pressed above the minimum threshold of 0.1 psi, they heard a perfectly contingent (zero delay) 550 ms trill of eleven 50 ms sounds of *random* frequency. Once the pressure crossed below the threshold, the trill continued for 550 ms. If no pressure on the pacifier above threshold occurred within 550 ms, the trill was interrupted. In other words, when oral pressure was applied above threshold, infants heard trills of random frequency sounds (not commensurate to oral pressure) until they crossed below the pressure threshold. The trill duration of 550 ms was determined on the basis that the rhythm of sucking activity is typically a maximum of two sucks per second by young infants. It controlled for possible instances of pressure going from below to above threshold without any auditory consequences, thus ensuring zero delay sound offset contingency for each threshold crossing, as for the analog condition, while providing infants with maximum auditory reinforcement. Preliminary tests based on five successive 2 s continuous and regular mechanical pressures and releases on the pacifier (0 to 0.6 psi maximum) indicated that the average sound frequency produced was 198 Hz (SD 50.6) with an intensity of 63–68 dB.

Note that the average sound frequency and intensity in both conditions corresponds to the average range of adult female speech sounds (Lieberman & Blumstein, 1988) and is well within the range of what is audible and preferred by infants from birth (DeCasper & Spence, 1991).

Procedure and coding

Infants were tested for a total of 9 minutes with the pacifier introduced in their mouth and the positive pressures they exerted on the pacifier were recorded on-line by the computer and the video camera (see technique above). Throughout testing, an experimenter gently held the pacifier in the infant's mouth for sucking. With the group of 2-month-olds, the experimenter wore a headphone, listening to music that prevented her from knowing which condition the infant was tested in. Such control was not possible with the newborns for safety reasons (e.g. prevention of choking). Another experimenter, not visible to the infant, monitored the computer and timed the conditions. During a first 90 s baseline, sucking activity was recorded while no auditory feedback was provided to the infant. This first baseline was followed by four successive 90 s experimental conditions of auditory feedback, either contingent but non-analog or contingent and analog (see description above). Each condition alternated in a counterbalanced order among the infants of each age group. Testing ended with a second 90 s baseline with no auditory feedback.

Sucking activity was coded on the basis of the on-line video recording (see technique above) which included the oral pressure variations applied by the infant on the pacifier, the recorded sound it produced, and a close-up frontal view of the infant. We analyzed sucking activity in the different conditions by 15 s blocks to capture a potential learning effect. Means and standard deviations of seven dependent measures were measured and compared to assess potential variations in the oral activity of the infant as a function of experimental conditions:

pressure amplitude: oral pressure on the dummy pacifier in pounds per square inch (psi)
standard deviation of amplitude: overall variability of the oral pressure amplitude
pressure width: oral pressure over time in seconds from the first to the second crossing of the threshold (0.1 psi, see above)
standard deviation of pressure width: overall variability of the oral pressure width
frequency of pressure above threshold: number of oral pressures crossing the 0.1 psi threshold or just at threshold
frequency of pressure just at threshold: number of oral pressures that were just at the 0.1 psi threshold
frequency of high pressure amplitude: number of oral pressures of 0.3 psi or above

For coding, a transparent grid was superimposed on the graphic representation of oral positive pressure variations on the TV monitor. The grid was segmented horizontally into six sections that corresponded to pressure from 0 to 0.6 psi. Each section was further segmented into four subsegments corresponding to a pressure scale of 0.025 psi. A horizontal dotted line corresponded to the threshold pressure for auditory feedback (0.10 psi). The dots at the level of the 0.10 psi threshold were 0.35 cm apart on the screen, corresponding to a tenth of a second of recording time. The time segment separating two dots was used as a unit for the measurement of pressure width of a suck above threshold. In other words, the width of each suck was determined by counting the number of dots that the pressure spanned between passing over the 0.10 psi threshold and crossing back over it. Each experimental condition was coded by independent observers, blind as to the experimental condition infants were in and the general rationale guiding the research.

Inter-observer reliability was assessed by comparing the scores of two independent coders for 20% of the infants in each condition. Pearson's r for all dependent measures was between 0.84 and 0.99.

Results

We proceeded by testing and analyzing each age group independently, first the 2-month-olds and later the newborns to see if we could replicate our findings with this younger group. For clarity of presentation, the two groups of infants are presented separately in the chronological order of the research. For each group, results obtained in the two baseline periods are considered first to capture any overall change in oral activity across testing, before and after exposure to contingent auditory feedback. We considered then the results obtained when comparing the first baseline period with the first experimental condition with contingent auditory feedback. This analysis was meant to capture any signs of differential oral responding when contingent sounds are first introduced to the infant. Finally, we compared the results obtained in the two experimental conditions (analog versus non-analog condition).

Group of 2-month-olds

Comparing the beginning and end baseline for each of the dependent measures treated separately, one-way analysis of variance (ANOVA) with repeated measures yielded a significant main effect of baseline periods with regard to the average width of pressure above threshold ($F(1, 17) = 4.64$, $p < 0.05$) and the standard deviation of pressure width ($F(1, 13) = 5.26$, $p < 0.04$). In both cases, these measures were significantly greater in the beginning baseline compared with the end baseline. These results suggest some familiarization across testing, infants generating more regular and less protracted pressures on the pacifier by the end of testing. Analyses of all other measures yielded no significant effect of baseline condition.

Regarding the comparison of oral activity during the first baseline period and the first experimental condition with contingent auditory feedback, 2 (condition: baseline vs experimental) × 2 (experimental trial: analog vs non-analog) ANOVA with repeated measures yielded a significant effect of condition for the frequency of high amplitude pressure ($F(1, 16) = 6.94$, $p < 0.02$) and a marginally significant effect of frequency of pressure just at threshold ($F(1, 16) = 3.71$, $p < 0.07$). For the other measures, no significant effects of condition were found. These results indicate that 2-month-olds did modulate their oral activity when introduced to contingent sounds for the first 90 s experimental test trial, whether these sounds were analog or non-analog (no significant condition × experimental trial interactions were found). In all, during the experimental condition of contingent auditory feedback, infants tended to generate more frequent pressures on the pacifier around the threshold associated with sounds, reducing significantly the frequency of high amplitude pressures.

For all dependent measures, no significant effect of time was found when entering the data by successive 15 s trial blocks as a repeated measure to capture within-trial response changes over testing time (see scoring above). This indicated no apparent effect of learning within a condition. For the following analyses, we collapsed the 15 s scoring blocks and further compared infants' oral activity in the successive experimental conditions based on a 2 (sequence: first vs second trial block) × 2 (experimental condition: analog vs non-analog) ANOVA with repeated measures for all dependent measures. This analysis yielded a main effect of experimental condition for the measure of frequency of pressure just at threshold (0.1 pressure, $F(1, 16) = 9.54$, $p < 0.007$) and no significant sequence × experimental condition interaction. The frequency of a low pressure, just at threshold, on the pacifier is greater in the analog compared with the non-analog condition (respectively, $M = 8.8$ and $M = 6.58$, $SD = 5.07$ and $SD = 4.24$). These results suggest that 2-month-olds did modulate their oral activity as a function of the relative congruence of the contingent sounds associated with sucking on the pacifier. In the analog condition, when the sound was commensurate to sucking, they tended to generate significantly more pressure just at threshold, and hence more restrained and controlled pressures on the pacifier.

Consistent with this trend, the same ANOVA of the average pressure amplitude above threshold yielded again a significant main effect of experimental condition ($F(1, 16) = 14.95$, $p < 0.002$) and no significant sequence × experimental condition interaction. The average pressure amplitude above threshold was greater in the non-analog compared with the analog condition (respectively, $M = 0.21$ and $M = 0.19$, $SD = 0.04$ and $SD = 0.04$). These results confirm again that 2-month-olds tended to modulate their oral activity as a function of the relative congruence of the contingent sounds associated with sucking on the pacifier.

ANOVA on the frequency of high amplitude pressure above threshold (0.3 psi or above) yielded a marginally significant main effect of experimental condition ($F(1, 16) = 4.12$, $p < 0.06$), infants generating more frequent high amplitude pressure on the pacifier in the non-analog compared with the analog experimental condition (respectively $M = 8.8$ and $M = 6.8$, $SD = 9.4$ and $SD = 9.0$). This marginal trend is consistent with the preceding results: 2-month-olds tended to generate more restrained and controlled pressure on the pacifier in the analog compared with the non-analog condition. Finally, ANOVA on the standard deviation of pressure amplitude yielded a marginally significant main effect of experimental condition ($F(1, 16) = 3.37$, $p < 0.08$), infants tending to show larger variability in pressure amplitude in the non-analog compared with the analog condition (respectively $M = 0.08$ and $M = 0.06$, $SD = 0.04$ and $SD = 0.02$). Again, this result is consistent with the enhanced restraint and control of oral activity in the analog condition.

Group of newborns

One-way ANOVA with repeated measures was performed for all dependent measures comparing the beginning and end baselines. The analyses yielded a significant main effect of baseline period regarding the standard deviation of pressure amplitude above threshold ($F(1, 13) = 14.26$, $p < 0.01$). The standard deviation of the pressure amplitude was significantly greater during the beginning baseline compared with the end baseline. Analyses of the standard deviation of the signal width for pressure above threshold yielded a marginally significant effect of baseline ($F(1, 13) = 4.68$, $p < 0.059$). Again, the standard deviation of the signal width tended to be greater during the beginning baseline compared with the end baseline. Analyses of all other measures yielded nonsignificant differences. The significant and marginal effects with regard to the standard deviations of the pressure amplitude and signal width suggest a familiarization with the pacifier across testing, infants generating significantly more regular oral pressure on the pacifier by the end of testing. This is consistent with what we found with 2-month-olds.

Regarding the comparison of oral activity during the first baseline period and the first experimental condition with contingent auditory feedback, 2 (condition: base-

Table 1

Dependent measure	Baseline 1	Analog	Non-analog	Baseline 2	*F*(condition)	*F*(baseline)
Newborns						
Pressure amplitude	0.14 (0.03)	0.14 (0.01)	0.14 (0.01)	0.14 (0.02)	0.122	2.2
SD pressure amplitude	0.040 (0.02)	0.04 (0.03)	0.04 (0.03)	0.03 (0.01)	0.322	14.26^{**}
Pressure width	3.82 (2.3)	2.80 (3.9)	3.9 (3.6)	3.2 (2.0)	0.023	3.40
SD pressure width	2.50 (2.6)	3.40 (4.3)	2.7 (3.3)	1.3 (1.3)	2.70	4.68
Frequency of pressure above threshold	30.07 (17.74)	30.5 (26.4)	30.7 (27.7)	32.35 (28.1)	0.132	0.67
Frequency of pressure at threshold	11.07 (7.09)	9.57 (9.5)	7.46 (6.7)	10.91 (5.0)	1.65	0.01
Frequency of high pressure amplitude	0.57 (1.6)	0.22 (0.42)	0.02 (0.47)	0.07 (0.27)	0.104	1.80
2-month-olds						
Pressure amplitude	0.19 (0.04)	0.21 (0.04)	0.19 (0.04)	0.20 (0.04)	14.95^{**}	0.194
SD pressure amplitude	0.07 (0.02)	0.06 (0.02)	0.08 (0.04)	0.07 (0.02)	3.37	0.168
Pressure width	3.65 (1.0)	3.46 (1.0)	3.34 (1.0)	3.04 (0.80)	0.35	4.64^{*}
SD pressure width	0.67 (1.4)	2.68 (1.8)	2.26 (1.3)	1.74 (1.0)	1.31	5.26^{*}
Frequency of pressure above threshold	52.05 (29.4)	56.0 (24.3)	53.8 (25.6)	60.6 (32.2)	0.90	1.21
Frequency of pressure at threshold	6.61 (3.91)	8.80 (5.0)	6.60 (4.2)	6.11 (3.46)	9.54^{**}	0.378
Frequency of high pressure amplitude	8.27 (9.42)	6.80 (9.0)	8.80 (9.4)	10.38 (10.54)	4.12	0.903

Notes: $^{**}p < 0.01$; $^{*}p < 0.05$.

line vs experimental) × 2 (experimental trial: analog vs non-analog) ANOVA with repeated measures for all dependent measures yielded no significant results. Newborns did not show any signs of differential oral activity during either of the experimental conditions with auditory consequences when compared with the first silent baseline period. These results indicate that newborns do not appear to modulate their oral activity when contingent auditory feedback is introduced during the first 90 s trial, whether this feedback is analog or non-analog.

For all dependent measures, no significant effect of time (15 s blocks) was found, demonstrating no apparent effects of learning within a condition. Again, for the following analyses, we collapsed the 15 s scoring blocks and further compared newborns' oral activity in the successive experimental conditions based on 2 (sequence: first vs second trial block) × 2 (experimental condition: analog vs non-analog) ANOVA with repeated measures for all dependent measures. These analyses yielded no significant main effect nor any significant interaction for any of the seven dependent measures. Overall, newborns did not show any evidence of a differential modulation of their oral activity in relation to the analog and non-analog conditions.

Groups of newborns and 2-month-olds compared

Table 1 provides a summary description of the results for each age group and in relation to all dependent measures, clearly indicating that only 2-month-olds showed some signs of an oral modulation as a function of the two experimental conditions. In comparison with 2-month-olds, *F* values for a main effect of condition for newborns are markedly reduced, none of them approaching even marginal significance.

As shown above, a major finding with 2-month-olds was their propensity to generate significantly more oral pressure just at threshold on the pacifier in the analog compared with the non-analog condition. They

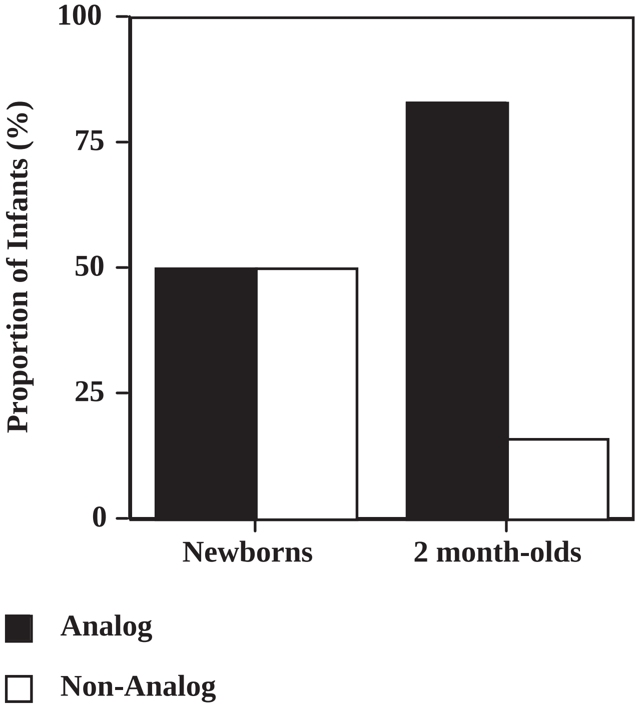

Figure 2 *Percentage of infants for each group (newborns versus 2-month-olds) that generated more frequent oral pressures 'just at threshold' in the analog compared with the non-analog condition.*

appeared to demonstrate more control and oral restraint in the former condition. Following our rationale, we view this differential responding as an index of infants' exploration of self-agency, in particular the exploration of the auditory analog of their own action. We assessed this trend across age by computing the number of infants for each group (newborns versus 2-month-olds) that, overall, generated more frequent oral pressures just at threshold in the analog compared with the non-analog condition. As illustrated in Figure 2 a marked proportion of 2-month-olds showed this trend (15 out of the 18 infants). In sharp contrast, the group of newborns showed an equal split among them (7 out of 14). Nonparametric statistics comparing these proportions across age groups confirmed the significance of this developmental trend ($\chi^2(1, 32) = 4.073$, $p < 0.05$).

Discussion

The empirical question guiding the research was whether 2-month-old infants and possibly newborns would demonstrate systematic modulation of their instrumental sucking response depending on contingent auditory feedback that was either analog or non-analog to the force they exerted on a dummy pacifier. As stated in the introduction, the question was not whether young infants could learn to suck in order to produce a sound, a well-documented fact. Rather, we asked whether infants from birth demonstrated that they can detect more than mere temporal contiguity between oral response and stimulus, systematically exploring the consequences of their own action. As a rationale, we reasoned that if infants would systematically modulate their oral activity as a function of contingent analog or non-analog auditory consequences, it would provide evidence that they are attentive to the relative matching between self-produced actions and their perceptual consequences. In turn, this attention would be an index of self-exploration and of the emerging sense of self-agency in early development.

Overall, results indicated that newborns did not show any evidence of a differential oral responding in relation to the conditions of contingent analog or non-analog auditory consequences. Despite this lack of oral response modulation, newborns did not merely act automatically on the pacifier. They showed some evidence of learning (familiarization) by generating less variable pressure amplitude on the pacifier during the second (final) baseline period, compared with the first. This result indicates that, as a function of testing, they familiarized with the pacifier which was new to them and eccentric in form and substance compared with the biological nipple. However, they did not show any signs of attention to the relative matching of self-produced action and its auditory consequences. In the context of this experiment and following our rationale, we conclude that newborn infants do not demonstrate self-exploration and do not provide any evidence of a sense of self-agency.

At first glance, the fact that newborns, aside from familiarization, did not show clear signs of response modulation as a function of conditions is not consistent with other findings demonstrating instrumental sucking abilities in neonates (Siqueland & DeLucia, 1969; Eimas *et al.*, 1971; DeCasper & Fifer, 1980; Walton, Bower & Bower, 1992). Note, however, that such demonstrations are based on the reinforcement of oral responses that are different from the one used here. Typically, neonates have been visually or auditorily reinforced based on specific intersuck or interburst intervals. In the present study, auditory consequences depended upon patterns and amounts of positive pressure applied on the pacifier. This procedural difference might account for the lack of instrumental learning evidenced in newborns. Nevertheless, there is still a possibility that the task in our experiment might have been too taxing for newborns, who might lack sufficient voluntary muscular control to explore the auditory consequences of their own sucking. In our view, this interpretation is unlikely given our observation that newborn participants, like 2-month-olds, showed a great amount of variability in positive pressures on the pacifier in the course of testing. This strongly suggests that newborns were capable of generating an adequate repertoire of exploratory pressures on the pacifier. What they apparently lacked was the ability to link their oral activity to the analog or non-analog patterns of auditory feedback. Finally, based on the rich oral pressure repertoire and active engagement of newborns, it does not appear that, compared with 2-month-olds, they lacked basic motivation to suck.

Like newborns, 2-month-old infants showed less variability in their oral pressure in the first compared with the second (final) baseline, suggesting that they too familiarized with the novel pacifier introduced in their mouth. As for newborns, we did not find any evidence of progressive learning as a function of experimental time. Our impression is that if infants noticed and acted on the functional link between their oral activity and the auditory consequences, they did that from the very beginning of testing. Within the time-frame of the experiment, we did not find any evidence of progressive learning or any significant learning curve for all our dependent measures. Again, this was true for both groups of infants.

In sharp contrast to the group of newborns, however, 2-month-olds demonstrated signs of attention to the relative matching of their oral action and the contingent auditory consequences. The main finding of the research is that by 2 months, in the condition where the auditory feedback matched their effort on the pacifier, infants spent more time exploring the threshold pressure at which contingent sounds start to be heard. Compared with the non-analog condition, in the analog condition 2-month-olds showed (1) significantly more frequent pressures on the pacifier just at threshold, (2) a significantly reduced average pressure amplitude, (3) a tendency toward less frequent high pressure amplitude, and (4) a tendency toward lesser variability of pressure amplitude. It is important to stress that the criterion for just at threshold oral pressure responses was stringent (pressure precisely hitting the threshold), reflecting a remarkable enhanced control of oral action on the pacifier in the analog condition providing commensurate auditory feedback.

In general, 2-month-old infants tended to be systematically more subdued and *controlled* in their oral action when the auditory consequences matched both spatially and temporally their instrumental effort on the pacifier. Again, this increased control was manifested from the beginning of testing, with no evidence of progressive learning. Following our rationale, this modulation of oral activity demonstrates that by 2 months, but not at birth, infants start to be attentive to the spatio-temporal characteristics of the perceptual (auditory) consequences of their own actions. They demonstrate systematic self-exploration and an emerging sense of self-agency.

Objections to this interpretation can be raised. One might be that the oral response modulation of 2-month-olds can be accounted for by the fact that the sounds heard in the analog or non-analog condition are differentially reinforcing. Accordingly, infants' responses would be more 'subdued' and controlled in the analog condition, because the contingent sounds are less arousing and reinforcing. In this case, we should expect more overall pressure responses in the non-analog compared with the analog condition. In fact, we found no difference in overall activity level (i.e. overall frequency of threshold crossing) between the two conditions, nor any evidence of differential learning.

Note that, in designing the experiment, we were careful to provide the more comparable auditory feedback in either condition in terms of possible range of frequency (Hz). In addition, the sound amplitude (dB) was carefully maintained constant across conditions. If infants heard a differential range of frequency between the two conditions, it was because they acted differently on the pacifier. Following the rationale of the study, the experimental paradigm was designed to control for the equivalence of temporal contingency between the two conditions, while varying the relative congruence between oral activity and auditory feedback across conditions. Attached to the paradigm, there is an inseparability of action and perception that cannot be teased apart for control. For example, one might object that infants attended and oriented to the sounds they heard independently of their oral activity, as if it was any sounds perceived regardless of their own action. The argument holds in relation to what we observe with newborns, but not with 2-month-olds. The fact that 2-month-olds appeared to modulate their oral responses as a function of the relative congruence of the auditory feedback indicates that they perceived the sounds as linked to their own action. They would not show any differential responding otherwise and, as we mentioned above, this differential responding does not seem to be accountable on the basis of differential arousal or reinforcement in either condition. Comparison with yoked control of analog or non-analog auditory feedback to test whether 2-month-olds do indeed perceive the sounds as linked to their own action would not allow us to control for the temporal contingency level in both conditions. Maintaining temporal contingency constant across conditions is necessary to assess whether infants explore the auditory consequences of their own actions beyond mere temporal contingency. Yoked control would introduce confusion between contingency detection and the relative spatio-temporal (proprioceptive–auditory) matching between self-produced action and its auditory consequences.

In both conditions infants controlled what they heard, but there was more control available in the analog compared with the non-analog condition. In the analog condition, infants were able to control both the frequency and the morphology of the contingent auditory event. In the non-analog condition, infants were able to control only the frequency of the contingent auditory event that otherwise was arbitrary in relation to the form of movement they exerted on the pacifier. In a sense, the non-analog condition should have been less reinforcing as it afforded relatively less control. However, we did not find any evidence of such differential reinforcement. Because the level of temporal contingency was identical in both conditions and because there was no apparent overall arousal differences in either condition (i.e. the same overall level of oral engagement), nor any evidence of differential reinforcement, the observed differences in oral activity modulation across conditions can be linked to infants' active matching of the auditory feedback with the proprioception of the effort they exerted on the pacifier. Again, because the level of contingency was comparable across conditions, infants appeared to explore more than just differences in temporal rhythm of auditory consequences.

If we consider the experimental situation as a problem-solving task in which infants tried to optimize the occurrence of sounds, each condition dictated a different strategy. In the non-analog condition, any pressure above threshold triggered a trill of random sounds. The crossing of threshold was what counted, not the pattern of pressure. In the analog condition, the pattern of pressure counted in addition to the crossing of the minimum pressure threshold. In other words, control was more at a premium in the analog condition. The differential oral activity of 2-month-olds across conditions reflected these particular constraints. They appeared to be more variable and less controlled (have less restraints) in their oral responding in the non-analog compared with the analog condition. In the non-analog condition infants engaged in more sucking-like activities of high amplitude pressure on the pacifier, interspersed with more disorganized patterns of pressure. This was reflected in the tendency towards a larger variability of pressure amplitude. In contrast, oral activity in the analog condition was more restrained, infants generating significantly more pressures just at or above threshold.

Finally, we might ask whether the matching of the crescendo–decrescendo sounds and oral pressure release in the analog condition played a role in the results we obtained with 2-month-olds. Future research might try to replicate our findings with, in the analog condition, discrete sounds that vary in frequency in an inverse pattern of decrescendo–crescendo commensurate with the contingent pressures applied on the pacifier. We anticipate that this variation will not affect our basic findings, infants probably picking up the invariant spatio-temporal correspondence between proprioception and audition which remains the same regardless of the order of ascending or descending sounds. This factor might specify more sophisticated intermodal correspondence, the origin of metaphoric perception (Wagner, Winner, Cicchetti & Gardner, 1981) or the detection of physiognomic aspects of stimulation (Werner & Kaplan, 1963). Such detection might start to play a role in later developmental stages, possibly with the emergence of symbolic functioning by the beginning of the second year (Bates, Benigni, Bretherton, Camaioni & Volterra, 1979). This assertion should be tested in the perspective of development with older infants and children.

At a more general level of interpretation, the emerging modulation of oral activity by 2 months of age indexes what we view as an important transition in the function of sensorimotor activity, in particular a transition from internal to external control of action. By 2 months, infants appear to adopt a new stance, a 'contemplative stance' to borrow from Werner and Kaplan (1999), guided by the systematic exploration of the consequences of their own action, on their own body, on objects, or on other people. We have tentatively coined this transition 'the 2 month revolution' (Rochat & Striano, 1999). An abundance of converging evidence exists in the infant literature, all pointing to such a transition by the second month in terms of emerging new behavioral state (i.e. alert activity; Wolff, 1987), emerging intersubjectivity via socially elicited smiling (Spitz, 1965), marked changes in the visual scanning and tracking of faces (Haith, Bergman & Moore, 1977; Bushnell, 1979; Johnson, Dziurawiec, Ellis & Morton, 1991), emerging discrimination between people and objects (Legerstee, Pomerleau, Malcuit & Feider, 1987), changes in motor and postural control (Hopkins & Prechtl, 1984) and changes in crying behavior observed in babies across cultures (Barr, Bakeman, Konner & Adamson, 1987).

Our findings corroborate the idea of a fundamental transition by the second month of postnatal development. It provides further support for the contention that, by 2 months, infants begin to manifest a functional decoupling of the perception–action cycle they display at birth as well as prenatally (Prechtl, 1984). This decoupling might correspond to the emergence of a contemplative stance in which infants start to engage in the exploration of their own body effectivities via a novel attention to the perceptual consequences of their own action. We propose that this transition toward systematic self-exploration is linked to the development of a new sense of self in infancy.

Acknowledgments

The authors wish to thank Lynda Reyes, Jane Yang and Hildie Cohen for the many hours they spent coding and analyzing the videotapes, and Eric Vanman for advice regarding statistics. We are grateful to the parents for allowing us to test their infants, as well as the nursing staff and administration at the Northside Maternity Hospital in Atlanta for their help and support. This research was supported by grant SBR-9507773 from the National Science Foundation awarded to P. Rochat.

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Received: 15 May 1998
Accepted: 4 November 1998