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SCIENCE DIRECT
Infant Behavior & Development 28 (2005) 266–289
Infant Behavior & Development

Haptic perception of material properties by 3-month-old infants

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Abstract

Three studies were conducted using a multiple trials procedure to investigate 3-month-old infants' ability to perceive material properties with their hands. In Study 1, infants discriminated stimuli which differed from one another in texture, temperature, compliance, and weight. In Study 2, infants discriminated stimuli which differed from one another only in weight. Infants evidenced discrimination by holding one stimulus longer than the other over trials, by involving both hands, and by increasing their general level of activity. A critical feature of both Studies 1 and 2 was that the stimuli were presented to infants in the pitch dark. In Study 3, infants were given the same stimuli as in Study 2, but under normal lighting conditions; they provided no robust evidence for discriminating the stimuli. We conclude that 3-month-old infants are able to perceive material properties, including weight differences, with their hands. However, they do so only under conditions which confine their attention, and they do not explore these properties with the specialized hand movements used by older infants and adults.

Keywords: Haptic perception; Infants; Attention

1. Introduction

Haptic perception of material properties by 3-month-old infants, one of the hallmarks of human behavior, is an inclination to examine and manipulate objects with the hands for the mere sake of exploration (e.g., Kellog & Kellog, 1933; Vauclair, 1984). This manual attention to objects is in keeping with the human interest in objects generally, and with special capacities relating to objects such as categorization, language, and tool-using. Indeed, features which are perceived with the hands may be critical to

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0163-6383/$ – see front matter
doi:10.1016/j.infbeh.2005.05.008

categorizing and naming some objects, and likewise perceiving certain features with the hands may be integral to effectively grasping and wielding them (cf., Johansson & Westling, 1984, 1987, 1988; Gordon, Forssberg, Johansson, & Westling, 1991). Given these important roles in human cultural activities, it is perhaps not surprising that manual exploration emerges and indeed is especially prevalent during infancy. By 4–5 months of age, infants are able to reach for and grasp objects effectively (see review by Bushnell, 1985) and they begin to show fingering and other manipulations with their hands shortly thereafter (i.e., Rochat, 1989; Thelen, 1979, 1981); these manual activities become increasingly focused, varied, and adept towards the end of the first year (Bushnell & Boudreau, 1993; Fagard, 1998; Lockman & McHale, 1989; von Hofsten & Siddiqui, 1993; Palmer, 1989; Ruff, 1984).

Researchers using a variety of methods have attempted to identify what information young infants actually obtain from their earliest manipulations of objects. The results from this body of literature initially present a mixed picture. In a series of studies, Streri and her colleagues have found that 4- and 5-month-old infants can haptically detect whether two components, one held in each hand, are rigidly connected or instead belong to two independent objects (Streri & Spelke, 1988, 1989; Streri, Spelke, & Rameix, 1993). Furthermore, infants were able to relate this information to a subsequently presented visual display. Similarly, Pineau, & Streri (1990) found that 4- to 5-month-olds could tactually discriminate different spatial arrangements of an object's three elements, and Streri (1987) and Streri and Pecheux (1986) found that 2- to 3-month-olds and 5-month-olds, respectively, could haptically discriminate a solid form (e.g., a disk) from the same form with a hole in its middle (e.g., a ring). However, Brown and Gottfried (1986) reported that 1-, 3-, and 5-month-olds provided no evidence for haptically discriminating any of four different pairs of shapes, and both Streri (1987) and Streri and Pecheux (1986) reported certain failures for intermodal transfer of the shape information they studied; interestingly, these failures were in opposite directions for 2- 3-month-olds (no vision to touch transfer) and 5-month-olds (no touch to vision transfer). Bushnell and Weinberger (1987) likewise found cross-modal asymmetries for both shape and texture information even on the part of infants as old as 11 months. Based on these results, they suggested that infants' haptic exploration is not as effective on its own as when it is "directed" by visual information.

Overall, then, the initial literature on haptic perception by young infants underscored an early ability to gather some kinds of information about objects with the hands alone, but raised questions and suggested limitations with regard to other types of information. Bushnell and Boudreau (1991) attempted to organize this array of results in a comprehensive review, which they also recently updated (Bushnell & Boudreau, 1998). As a framework, they relied on the adult perception work of Klatzky and Lederman (1993, 1995) (Klatzky, Lederman, & Metzger, 1985; Klatzky, Lederman, & Reed, 1987; Lederman & Klatzky, 1987, 1990), who have established that haptic perception of particular object properties is closely linked to specific hand movements or "exploratory procedures". For example, adults perceived texture most precisely when they were permitted to move their hands in a lateral gliding motion across the surface of stimulus objects, and furthermore they spontaneously engaged predominantly in this pattern of movement when asked to make judgements about the texture of objects. Similarly, squeezing or poking hand movements correspond to perceiving the compliance (hardness) of objects, and hefting or lifting objects away from a supportive surface corresponds to perceiving their weight. Bushnell and Boudreau identified the sorts of hand movements infants are capable of making at various ages from the motor development literature, and then, following Lederman and Klatzky (1987, 1990), reasoned that these might constrain the types of object properties infants perceive at the corresponding ages. They analyzed studies of infant haptic perception according to the object properties contrasted in the stimuli in each case, and found that the pattern of positive and negative results across age generally fit the predictions derived from considering infants' motor abilities.

In their review, Bushnell and Boudreau (1991, 1998) also identified several important lacunae and distinctions within the infant perception literature. They noted, for instance, that many studies actually address either cross-modal or bimodal perception rather than purely within-mode haptic perception. They also pointed out that most of the research with young infants has involved spatial object properties such as shape and object unity, rather than material properties such as temperature, compliance, and weight. This focus is especially noteworthy in light of Klatzky and Lederman's suggestion that in contrast to vision, the hands are especially adapted to perceive material properties. These properties may be accurately perceived with relatively simple and quickly executed hand movements, in contrast to spatial properties such as configurational shape whose haptic perception demands more intricate and extended hand movements. Thus, one might expect that material properties might be more readily perceived than shape, for example, by young infants with limited motor abilities, and yet these have received rather little attention in the literature. Finally, Bushnell and Boudreau argued that some of the shape stimuli which have been employed with infants may actually boil down to something else. For instance, with the solid forms and forms with a hole in the middle used by Streri (1987) and Streri and Pecheux (1986), Bushnell and Boudreau noted that these would necessarily be gripped with different postures of the hand, so that infants' discrimination of them could reflect a sensitivity to body position or "muscle memory" rather than representations of shape per se. Streri, Lhote, and Dutilleul (2000) also called attention to such a "motor hypothesis" that might account for certain early abilities, in contrast to genuine haptic perception which involves the integration of cutaneous and kinaesthetic information.

Several investigations appear to address the gaps and issues raised by Bushnell and Boudreau (1991, 1998). Rochat (1987) found that newborn infants as well as 2- and 3-month-olds responded differently to hard versus soft (spongy) objects which were otherwise identical. When these objects were placed in the infants' hands, they squeezed the hard object more frequently and released their pressure on it more abruptly than with the soft object, as though they were constantly "regripping" the hard object. Similarly, Molina and Jouen (1998) found that newborns applied different patterns of manual pressure to a smooth versus a granular stimulus. The smooth stimulus was held with a higher continuous pressure in comparison to the granular stimulus, but the granular stimulus evoked higher discrete, "peak" pressures. However, in both Rochat's and Molina and Jouen's studies, infants participated in a single trial with just one or the other of the stimuli, and the distinct responses to the stimuli were evident at the beginning of the trials and remained constant throughout. Such within-trial results indicate the presence of sensory mechanisms differentially responsive to the stimulus contrasts involved, but they do not document representation, memory, or comparison of the stimulus qualities as habituation or responses to stimulus changes across trials would. Accordingly, Molina and Jouen conclude that their results "reflect a modulation of a basic reflex mechanism in which the activity of the hand is triggered by the characteristics of the stimulation" rather than "part of a perception-action cycle" or "manipulation per se" (p. 665), and the same would apply to Rochat's results. Thus, whether young infants can genuinely perceive material properties such as compliance, texture, temperature, etc., still remains in question.

Streri et al. (2000) used a procedure specifically designed to reveal information processing as distinct from motor fatigue or stimulus-triggered reflex modulations. They presented newborns with either a cylinder or a same-sized rod with a triangular cross-section. Infants were given the initial stimulus repeatedly until the duration of holding decreased to a criterial level, and then were given the alternative stimulus. With both stimuli, infants showed a novelty response, holding the alternative stimulus on the test trials for significantly longer than they held the originally given stimulus on the final trials with it. Based on these results, Streri et al. conclude that young infants are able to "process, encode and retain, and discriminate some information about object shape" (p. 326) with the hands, although they also acknowledge that neonates may not be able to process shape "completely"—that is, there may be some aspects of shape which neonates cannot process and discriminate due to the integration and synthesis required in working memory. The aspect of shape which neonates were able to discriminate in Streri et al.'s study was that of smoothly curved versus sharply angled.

In the research presented below, we used a procedure similar to that of Streri et al., in order to investigate whether young infants can perceive and discriminate material properties with their hands. In three separate studies, we evaluated the behavior of 3-month-old infants, aiming to examine haptic perception of material properties at an age prior to when infants engage in fingering and other intricate exploratory movements. Objects which were all held with the same kind of grip were used as stimuli, so that they could not be discriminated on the basis of hand posture. In Studies 1 and 2, these were presented to infants in the pitch dark throughout the procedure, so that neither interference nor assistance from vision or cross-modal perception was a factor. Finally, a multi-trial procedure involving changes of stimuli for at least some groups of infants was employed, to distinguish full-fledged haptic perception from stimulus-triggered reflex modulations. In the first study, we examined whether infants can discriminate with their hands two identically shaped objects that varied in several material properties, namely compliance, temperature, texture, and weight. In the second study, we considered whether infants discriminate identically shaped objects that differed solely in weight. The third study was designed to control the possibility that infants' discrimination of weight in Study 2 was due to biomechanical limitations.

2. Study 1

2.1. Method

2.1.1. Participants

Twenty-four 3-month-old infants (*M* = 3 mos, 4.2 dys; range = 2 mos, 23 dys to 3 mos, 14 dys), 13 males and 11 females, were included in the final sample. Fifteen additional infants were also tested but not included in the final sample, four because of experimenter error, seven because they became fussy before completing at least four trials, three because they refused to hold the stimulus objects, and one because of interference by a sibling. The infants were recruited by mail solicitation based on the birth records of several communities in the Boston area. Respondents to the mail solicitation are predominately white, middle-class, two-parent families. All of the infants were healthy and born full-term (greater than 38 weeks gestational age and with a birth weight of 2500 g or more) according to parental reports. The infants were tested individually in a university laboratory in the presence of a parent, who had provided informed written consent.

2.1.2. Stimuli

The stimulus objects were small "dumbbells" 13–14 cm long (see Fig. 1). Each dumbbell was comprised of a shaft 5–6 cm long and 1.3 cm in diameter made from either a metal spring or a sponge hair curler; this was the portion of the stimulus which was placed in infants' hands. At each end of the shaft, there was a sponge Nerf ball 4.2 cm in diameter. These were included so that infants' faces were protected if

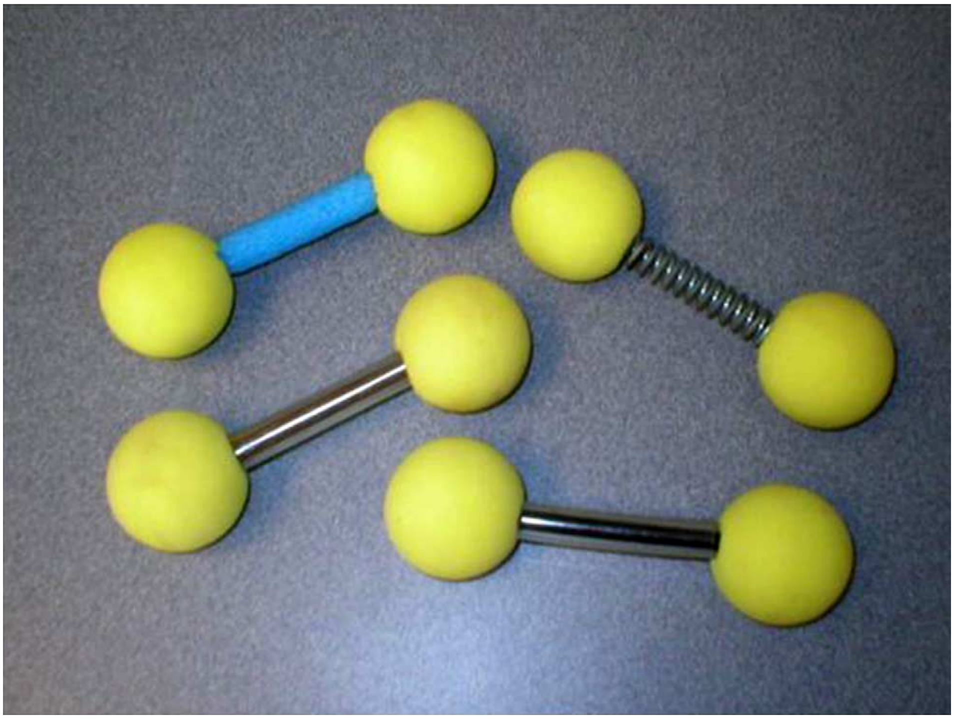

Fig. 1. The "dumbbell" stimuli used in Studies 1–3. The curler and spring stimuli used in Study 1 are shown at the top left and right, respectively. The heavy and light stimuli used in Studies 2 and 3 are shown at the bottom left and right, respectively.

they bumped them with the stimuli. The Nerf ball ends also ensured that the stimuli were identical if infants raised them to the mouth and explored them orally; only the shaft portion gripped and covered by the hand was different for the two stimuli. The spring (S) and curler (C) shafts were the same size and cylindrical shape, but differed from one another in texture – the spring was ridged and the curler was smooth, in temperature – the spring was cool and the curler was warm, in compliance – the spring was rigid and the curler was compressible, and in weight – the spring with two Nerf balls weighed 27 g and the curler with two Nerf balls weighed 9 g. Thus, the stimuli were designed to assess manual rather than oral discrimination of material as opposed to structural object properties.

2.1.3. Physical arrangement and equipment

Infants were video-taped while holding the stimulus objects in the pitch dark. Although some infants may have become fussy and unable to complete the procedure on account of the darkness, infants' general behavior when tested in the dark was comparable to when they were tested in the light (see Study 3 below). Anxiety due to the darkness seemed minimal, perhaps because of the brevity of the session and because infants were in physical contact with their caregiver throughout the procedure. Each infant sat upright on a parent's lap, straddling the parent's right thigh and facing an experimenter (E1) who sat on the floor at the parent's feet. This posture approximates the way infants are sometimes held by an adult interacting with another person, with the infant seated facing "outwards" and supported against the caregiver's torso, and infants seemed comfortable and unperturbed by this arrangement. The vertical seating arrangement allowed infants to freely move their arms and hands and insured that if they let go of the stimulus, it would drop to the floor (rather than remain available resting on the infant's chest, e.g.). Parents were instructed to support their infants around the waist and to remain still and quiet throughout the procedure. Because it was dark, parents did not know which stimulus the infant was holding on any given trial. A small glow-in-the dark Band-Aid was placed on the infant's right shoulder so that E1 could locate the infant's hand in the dark in order to present the stimulus.

A pair of infra-red light fixtures hung from the ceiling approximately 150 cm above the infant and illuminated the infant and surrounding area with infra-red light. An infra-red sensitive video camera was positioned about 30° to the right and 100 cm away from the infant. This camera was connected to a VCR for recording the infant's behavior for later analysis; the video signal was also fed through to a camcorder which a second experimenter (E2) looked into and thus monitored the infant's behavior on-line. This experimenter marked the beginning and end of each trial by operating a push-button according to when infants first gripped and then released the stimulus. The push-button was interfaced to a PC, which kept track of infants' holding times for each trial and emitted a signal if a trial reached the maximum duration and the infant had not yet released the stimulus.

2.1.4. Procedure and design

Once the parent and infant were comfortable and everyone was in the appropriate positions, the room lights were turned off and the experimental session began. E1 uncovered the stimuli from a box next to her and selected the one designated for the infant's first trial. She took hold of the infant's right hand and put the stimulus object into it, placing the shaft between the infant's thumb and fingers and wrapping the infant's fingers around the shaft if the infant did not grasp the shaft spontaneously. E1 then took her hand away from the infant's and E2 initiated the trial upon seeing that the infant was holding the object independently. If the infant dropped the stimulus after holding it for less than 3 s, E2 announced that this had occurred and the trial was repeated; that is, the same stimulus was presented again and the timing was started over. Once the object had been held for at least 3 s, infants were permitted to continue to hold and freely explore the stimulus until they dropped it, or until the computer signalled that 25 s had passed. E2 could see in the camcorder if the infant had dropped the object and hear from the computer if 25 s had passed, and she announced when the trial had ended one way or the other. E1 then retrieved the stimulus if the infant was still holding it, E2 reset the computer, and then the next trial in the sequence was presented in the same fashion.

Infants were presented the spring and curler stimuli in one of four predetermined sequences. Infants in the constant condition were presented four successive trials with the spring (SSSS) or four successive trials with the curler (CCCC). Infants in the alternating condition received four alternating trials with the spring and curler, starting with either the spring (SCSC) or the curler (CSCS) first. Six infants, three males and three females, were tested with each of the four sequences, except for the CSCS sequence for which there were four males and two females. The original design called for each infant to be presented with an additional four trials in the opposite condition following the completion of the first four trials. However, fewer than half the infants completed all eight planned trials, so ultimately only the first four trials for each infant were scored and analyzed.

2.1.5. Measures and scoring

The videorecords for each trial were scored for four measures: duration, mouthing, two-handed involvement, and activity level. Duration was the straight-forward amount of time in seconds that the infant held the stimulus. Because of the procedural stipulations, duration could range from a minimum of 3 s to a maximum of 25 s. Mouthing was defined as the infant's bringing the stimulus to the mouth or cheek area and sucking on the object itself or on the hand which held the object. Mouthing was scored on a 3-point rating scale: 0 if there was none at all in the trial; 1 if there were between one and three brief, non-intense episodes; and 2 if there were more than three brief episodes or a single sustained episode. Two-handed involvement was defined as the infant's passing the stimulus from one hand to the other or bringing the second hand in to hold the hand which held the object or to hold the object itself with two hands. Like mouthing, two-handed involvement was scored on a 3-point rating scale: 0 if there was none at all in the trial; 1 if there were between one and three brief, non-intense episodes; and 2 if there were more than three brief episodes or a single sustained episode.

Activity level was assessed with a system designed to capture the extent to which the infant moved the stimulus, as in waving, banging, hefting, lifting, etc. A grid of horizontal lines was placed over the image of the infant's body on the television monitor. This grid was "body-scaled" for different-sized infants such that from one "anchor" line positioned on the infant's shoulder, there were four more lines down to another "anchor" line positioned at the infant's knuckles when the stimulus was gripped with the arm hanging down to the side. The number of grid lines crossed by the top end of the stimulus throughout each trial was counted, and this number of "crossings" was divided by the trial's duration to yield the activity level score.

The video data were scored by two observers, each of whom scored the trials for approximately half of the subjects. A randomly selected subset of 22 trials (23% of the data) were independently scored by both observers so that interobserver reliabilities could be computed. Pearson correlations between the two observers' scores for these trials were 0.92, 0.89, 0.92, and 0.99 for duration, mouthing, two-handed involvement, and activity level, respectively.

2.2. Results

The scores for each of the four measures were subjected to a condition (constant versus alternating) by first-stimulus (curler versus spring) by trials Analysis of Variance. For both mouthing and two-handed involvement, the analyses yielded no significant effects or interactions. Overall, these behaviors were relatively rare and variations seemed to be a matter of individual differences. On the 0–2 rating scales, the mean score for mouthing was 0.51, and for two-handed involvement, it was 0.50. Within each condition and for each stimulus, there were several infants who never exhibited mouthing at all and one or two who did so on nearly every trial. Likewise, within each experimental group, there were several infants who never involved the second hand at all and a couple who did so on nearly every trial.

The initial analysis on durations yielded a significant condition × first-stimulus × trials interaction, $F\ (3,60) = 6.03$, $p = 0.001$. The trials effect was also marginally significant, $F\ (3,60) = 2.54$, $p = 0.065$, as was the first-stimulus × trials interaction, $F\ (3,60) = 2.70$, $p = 0.054$. To explore these results further, separate first-stimulus × trials analyses of variance were conducted for the two conditions. For the constant condition, there was a significant first-stimulus × trials interaction, $F\ (3,30) = 7.05$, $p = 0.001$. The mean durations for each constant stimulus group and each trial are shown in Fig. 2a. As can be seen from the figure, infants given the curler repeatedly tended to increase the duration of holding it as the trials progressed, while infants given the spring repeatedly tended to decrease the duration of holding it across trials. Post hoc analyses showed that infants given the curler repeatedly held the stimulus for shorter durations on the first trial, $t\ (10) = 2.69$, two-tailed $p = 0.023$, and for longer durations on the fourth trial,

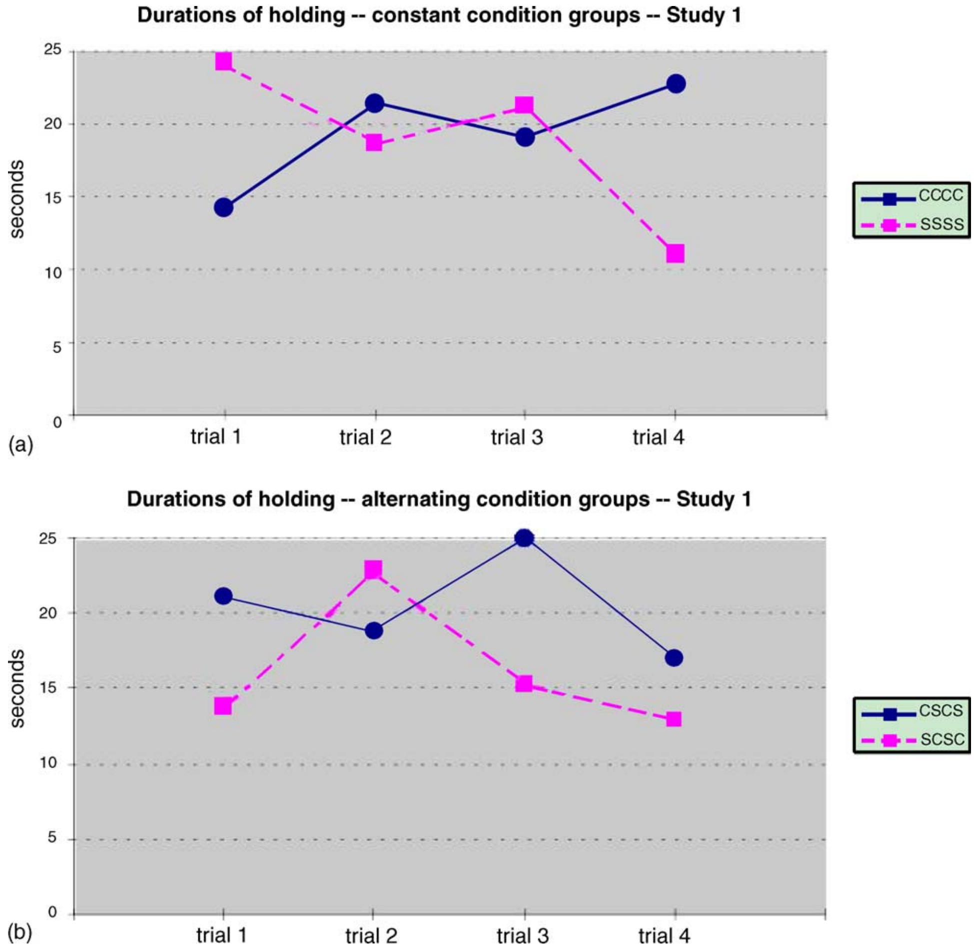

Fig. 2. The mean durations of holding on each trial for each stimulus group in Study 1. (a) The two constant condition groups. (b) The two alternating condition groups.

t (10) = 2.99, two-tailed $p = 0.013$, than infants given the spring repeatedly. The durations of holding did not differ for the two stimulus groups on the second and third trials.

For the alternating condition, the first-stimulus × trials interaction was marginally significant, F (3,30) = 2.34, $p = 0.095$. The mean durations for each alternating stimulus group and each trial are shown in Fig. 2b; as the figure shows, infants in both alternating groups tended to hold the curler for longer durations than the spring. To examine this within-subject stimulus difference, the total duration holding the curler (trials 1 and 3 for some infants, trials 2 and 4 for others) and the total duration holding the spring (likewise trials 1 and 3 for some infants, trials 2 and 4 for others) were computed for each infant in the alternating condition. These durations were compared with a dependent samples t-test, which confirmed that infants who experienced both stimuli tended to hold the curler for longer durations than the spring, t (11) = 2.11, two-tailed $p = 0.059$.

Thus, the duration results for both conditions reveal a sort of "preference" for the curler over the spring stimulus. In the constant condition, infants given the curler stimulus tended to hold on to it longer and

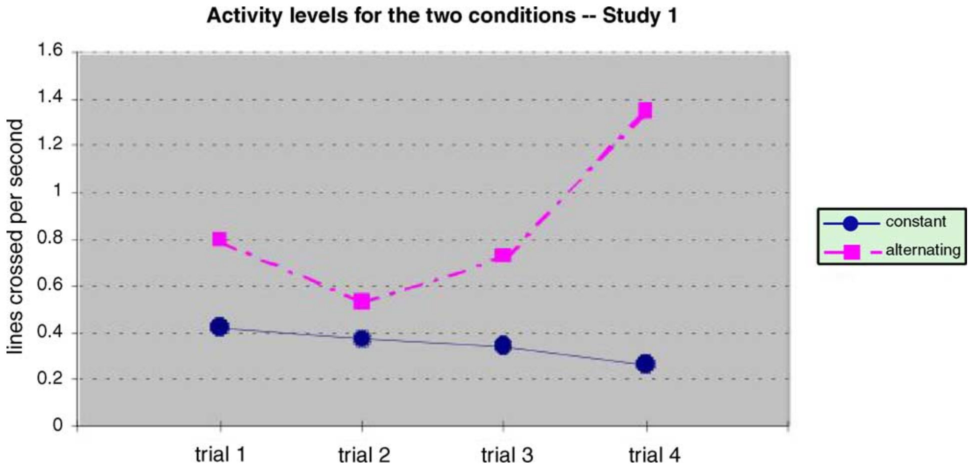

Fig. 3. The mean activity levels on each trial for the two conditions in Study 1.

longer as trials progressed, while infants given the spring stimulus tended to hold on to it shorter and shorter over trials. In the alternating condition, infants held the stimulus for longer durations on the trials they were given the curler than on the trials they were given the spring.

For the activity level measure, the initial three-way ANOVA yielded a significant main effect of condition, $F\ (1,20) = 5.06$, $p = 0.036$, and also a significant condition × trials interaction, $F\ (3,60) = 3.98$, $p = 0.012$. The main effect of trials was also marginally significant, $F\ (3,60) = 2.21$, $p = 0.097$. None of the effects or interactions involving first-stimulus were significant. The mean activity levels for the two conditions across trials are shown in Fig. 3. As can be seen from the figure, infants in the alternating condition (the CSCS and SCSC groups) were more active overall than infants in the constant condition (the CCCC and SSSS groups), and they became especially active on the last trial, whereas infants in the constant group became slightly less active as the trials progressed. Post hoc analyses showed that infants given the two stimuli alternately were marginally more active on the third trial, $t\ (22) = 1.88$, two-tailed $p = 0.074$, and significantly more active on the fourth trial, $t\ (22) = 2.75$, two-tailed $p = 0.012$, than infants given the same stimulus repeatedly. The activity levels for the two conditions did not differ on the first and second trials.

2.3. Discussion

The results for Study 1 show that infants were able to perceive the difference between the spring and curler stimuli. Infants given the curler stimulus repeatedly tended to hold it for increasing durations over trials, while infants given the spring stimulus repeatedly tended to hold it for decreasing durations. Likewise, infants given the spring and curler on alternate trials held on to the curler for longer durations than the spring, and they also became more active over trials than infants given the same stimulus over and over again. Furthermore, infants must have discriminated the stimuli haptically, that is, by contacting them with their hands alone. The stimuli were presented in the pitch dark and thus were not visible, and the portions of the stimuli which could be touched with the mouth were not different.

The spring and curler stimuli differed from one another in texture, temperature, compliance, and weight. Thus, it is not clear which of these properties, or which combination of them, served as the basis for infants' discriminating the stimuli. Nevertheless, these results provide the first evidence of haptic perception of any of these material properties on the part of infants younger than 6 months. There are previous reports that neonates' grasps are modulated according to the compliance (Rochat, 1987) and the texture (Molina & Jouen, 1998) of the stimulus objects. However, the differential responses in these studies were present immediately and also throughout a single exposure to the stimulus. Thus, as Molina and Jouen conclude, they probably represent stimulus-triggered accommodations of the grasp reflex rather than subject-controlled activities based on perceived information. In contrast, the across-trials effects found here must have entailed memory for and comparisons of haptic information, and therefore genuine perception of material properties.

Other instances of haptic perception by very young infants have involved stimuli differing in structural properties such as size, shape, or object unity (cf., Streri & Milhet, 1988; Streri & Spelke, 1988, 1989). Discrimination of the stimulus variations in most of these studies could have been based on "muscle memory", that is, on recognition of the hand postures used to hold the stimuli (cf., Santello, Flanders, & Soechting, 1998) or of the linked versus independent movements of the two hands. The stimuli employed here did not differ in any structural properties and afforded identical hand postures and arm movements. Similarly, Streri et al. (2000) employed shape stimuli designed to rule out the "motor hypothesis" for haptic recognition. They found that neonates were able to discriminate a small cylinder from a similar-sized rod having a triangular cross-section. Even infants who merely grasped the stimuli (i.e., did not move their fingers across them) made this discrimination, so it was most likely mediated by cutaneous "edge detectors" in the palm of the hand; these would have been active with the rod but not with the cylinder. The spring-curler discrimination observed here may be based on the same mechanism, as the coils of the spring could stimulate such edge detectors while the smooth surface of the curler would not. Alternatively, cutaneous receptors registering temperature, pressure (for the compliance difference), or shearing (for the weight difference) could have mediated discrimination of the spring and the curler.

Regardless of what specific mechanism mediates this ability, the results of Study 1 show that material properties can be haptically perceived by infants as young as 3 months old. At this age, infants do not engage in intricate, controlled finger movements or asymmetrical bimanual activities when handling objects (Bushnell & Boudreau, 1993; Fagard, 1998; Rochat, 1989; Ruff, 1984). The fact that young infants can nevertheless perceive material properties even without complex exploratory procedures is commensurate with the idea that the haptic modality is uniquely tuned for apprehending material properties. Psychophysical research indicates that adults can likewise perceive and discriminate temperature, compliance, weight and sometimes texture in "a haptic glance", and with just simple enclosures, static contact, and unsupported holding of objects (Klatzky & Lederman, 1995; Lederman & Klatzky, 1987).

It is interesting that infants did not differentiate the two stimuli with behaviors often identified as early means for exploring objects, namely, with mouthing or involving the second hand. Instead, the clearest evidence for discrimination seemed to develop over trials. Infants in the alternating groups were not initially more active than those in the constant groups, but *became* more active as the trials progressed, and infants repeatedly given the spring versus the curler did not differ in their overall durations of holding but in the direction of change over trials. These "cumulative" effects may reflect the fact that haptic information requires substantial exposure time for infants to process, for instance, in comparison to visual information as demonstrated by Streri and Pecheux (1986). Processing haptic information may also require multiple first-contacts (thus multiple trials in our procedure) because the information is at least partially conveyed by the responses of fast-adapting mechanoreceptors. Finally, the cumulative effects we observed are also consistent with Lewkowicz's (1991) idea that young infants process information of all kinds only in terms of overall levels of intensity or variability, as degrees of "arousingness". Thus, infants in the alternating groups were exposed to greater stimulus variability over trials, leading ultimately to higher levels of arousal which were reflected in the higher activity levels seen on the final trials.

If infants instead discriminated the spring and curler on the basis of a more specific object property, their behavior is arguably most related to either temperature or weight. Infants in the alternating groups may have held onto the spring for shorter durations than the curler – that is, let go of it sooner – because it was more uncomfortable (colder) or fatiguing (heavier) in comparison to the curler. And their increased activity in contrast to the behavior of infants in the constant groups could be construed as rudimentary "hefting" or attempts to explore the variations in weight. Given the positive results of Study 1, it seemed appropriate to narrow the field and proceed to investigate infants' haptic abilities with stimuli contrasting on just one dimension rather than on multiple material properties. Because of the suggestions in their behavior that infants in Study 1 may have been attending to weight, we chose to explicitly focus on this object property with all others held constant in Study 2.

3. Study 2

In Study 2, infants' responses to stimuli differing only in weight were examined. Weight was one of the several properties in which the stimuli in Study 1 differed, so it could have been a basis for the discrimination infants showed in Study 1. Furthermore, weight perception has not heretofore been investigated in infants as young as 3 months. Observations in the literature generally indicate that infants may perceive differences in weight by 8 or 9 months, but not at younger ages (cf., Itier, Provasi, & Bloch, 2001; Mounoud & Bower, 1974; Palmer, 1989; Ruff, 1984). However, all of the prior studies on infants' perception of weight were conducted in the light, with vision as well as haptic exploration also available. Bushnell and Boudreau (1991, 1998) have speculated that under these conditions, object properties available to both modalities (such as texture, size, and shape) may be most salient and thus weight may receive little or none of infants' limited attention. In contrast, the procedure here was conducted in the pitch dark, so in effect all properties are unimodal and weight might therefore capture a fairer share of infants' attention. Infants also did not have to lift the stimuli from a surface in order to perceive weight in our procedure because they sat upright with their hands hanging freely in space, they were automatically working against the force of gravity as soon as they grasped the objects.

3.1. Method

3.1.1. Participants

Twenty-four 3-month-old infants (*M* = 2 mos, 28.5 dys; range = 2 mos, 20 dys to 3 mos, 9 dys), 14 males and 10 females, were included in the final sample. Eight additional infants were also tested but not included in the final sample, one because of experimenter error, five because they became fussy before completing at least four trials, and two because they refused to hold the stimulus objects. The infants were recruited by the same procedure and from the same population as for Study 1. All of the infants were healthy and born full-term (greater than 38 weeks gestational age and with a birth weight of 2500 g or more) according to parental reports. The infants were tested individually in a university laboratory in the presence of a parent, who had provided informed written consent. None of the infants participating in Study 2 had previously participated in Study 1.

3.1.2. Stimuli

The stimulus objects were small dumbbells similar to those employed for Study 1. However, instead of the spring or curler, the shaft of each stimulus for Study 2 was made from plastic hollow tubing 12 mm in diameter and stuffed with a wooden rod. Thus, the stimuli were all smooth, rigid, and warm (non-metallic), as well as identical in size and shape. The stimuli for Study 2 differed only in weight. The "heavy" dumbells weighed approximately 52 g, while the "light" dumbells weighed approximately 16 g. The weight difference was created by embedding two standard copper pennies into the Nerf ball at one end of the heavy stimuli; no pennies were embedded into the light stimuli. The heavy and light stimuli are shown in Fig. 1.

3.1.3. Physical arrangement, equipment, and procedure

The physical arrangement, equipment, and general procedure for Study 2 were identical to those described for Study 1. Thus, infants sat straddling a parent's knee in the pitch dark and were handed a series of the dumbbell stimuli one at a time. They were permitted to freely explore each stimulus until they dropped it or until 25 s had passed, at which point the next stimulus in the series was presented. Each infant's behavior throughout the session was filmed via an infrared-sensitive video system.

3.1.4. Design, measures, and scoring

The design for Study 2 was similar to that employed for Study 1. Infants were presented the heavy and light stimuli in one of four predetermined sequences. Infants in the constant condition were presented four successive trials with the heavy (HHHH) or four successive trials with the light (LLLL) stimulus. Infants in the alternating condition received four alternating trials with the heavy and light stimuli, starting with either the heavy stimulus (HLHL) or the light stimulus (LHLH) first. Six infants were tested with each of the four sequences. In the two Constant sequences, there were three males and three females, while in the two Alternating sequences, there were four males and two females. The original design called for each infant to also be presented with four more trials in the opposite condition following the completion of the first four trials. However, only 11 infants completed all eight planned trials, so the principal analyses were conducted on just the first four trials.

The video records for each trial were scored for the same four measures as in Study 1, that is, duration, mouthing, two-handed involvement, and activity level. These were scored in the same manner and with the same definitions as before. Each trial for each infant was scored by two observers working independently. The average of the two observers' scores for each measure was used in the statistical analyses. If the two observers' scores differed by 2 units for mouthing or two-handed involvement, by 2 s for duration, or by 20% for the number of crossings used to compute activity level, the trial in question was scored by a third observer and the two closest scores were used to compute the average used in the analyses. Such adjudication was needed for just 9 of the 96 trials scored for Study 2, and concerned the number of crossings in every instance.

3.2. Results

The scores for each of the four measures were subjected to a condition (constant versus alternating) by first-stimulus (heavy versus light) by trials Analysis of Variance. The analysis for mouthing yielded a significant main effect of condition, F (1,20) = 5.09, p = 0.036. There were no other significant effects or interactions. Infants in the alternating condition did more mouthing overall (M = 0.66) than infants in the constant condition (M = 0.19). However, this was true across all four trials, including the first one, which suggests that the condition effect is probably spurious. As in Study 1, mouthing was relatively rare overall (grand M = 0.42 on the 0–2 rating scale), with many infants never mouthing at all but a few who mouthed on nearly every trial. In Study 2, there were five such infants (frequent mouthers) in the alternating condition but only one in the constant condition; these individual differences probably generated the condition effect.

The initial analysis for two-handed involvement yielded a significant condition × trial interaction, F (3,60) = 2.93, p = 0.041. There were no significant main effects or other interactions. As is shown in Fig. 4, infants in the constant condition tended to decrease the degree of two-handed involvement over trials, whereas infants in the alternating condition tended to increase it. Post hoc analyses indicated that infants in the alternating condition engaged in more two-handed involvement than infants in the constant condition on the fourth trial, t (22) = 2.130, two-tailed p = 0.045. Two-handed involvement for the two conditions was not different on any of the first three trials. As in Study 1, two-handed involvement was relatively rare overall (grand M = 0.32 on the 0–2 rating scale), with about half the infants in each condition exhibiting none of this behavior at all.

The initial analysis of durations yielded a significant condition × first-stimulus interaction, F (1,20) = 5.62, p = 0.028, and also a significant condition × first-stimulus × trials interaction, F (3,60) = 3.95, p = 0.012. There were no significant main effects or other interactions. To explore these results further, separate first-stimulus × trials analyses of variance were conducted for the two conditions. For the constant condition, this secondary analysis yielded a main effect of first-stimulus, F (1,10) = 9.69, p = 0.011. The mean durations for the two constant stimulus groups and each trial are shown in Fig. 5a.

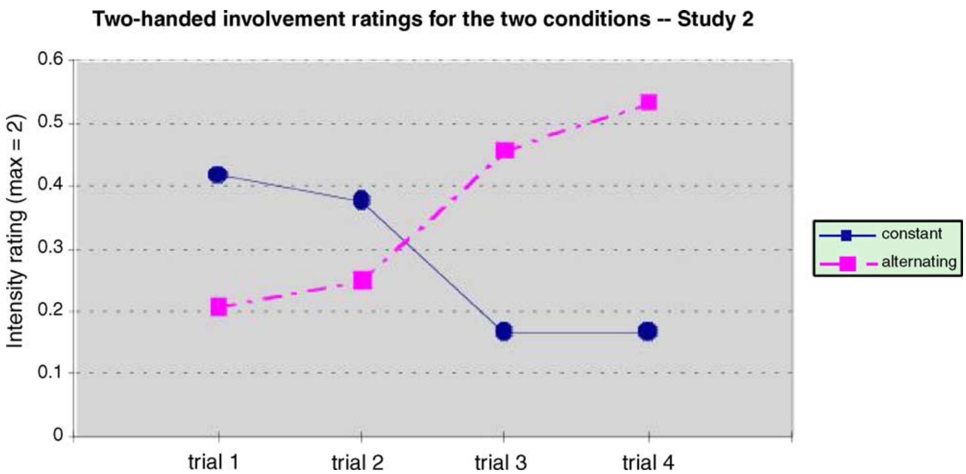

Fig. 4. The mean ratings for two-handed involvement on each trial for the two conditions in Study 2.

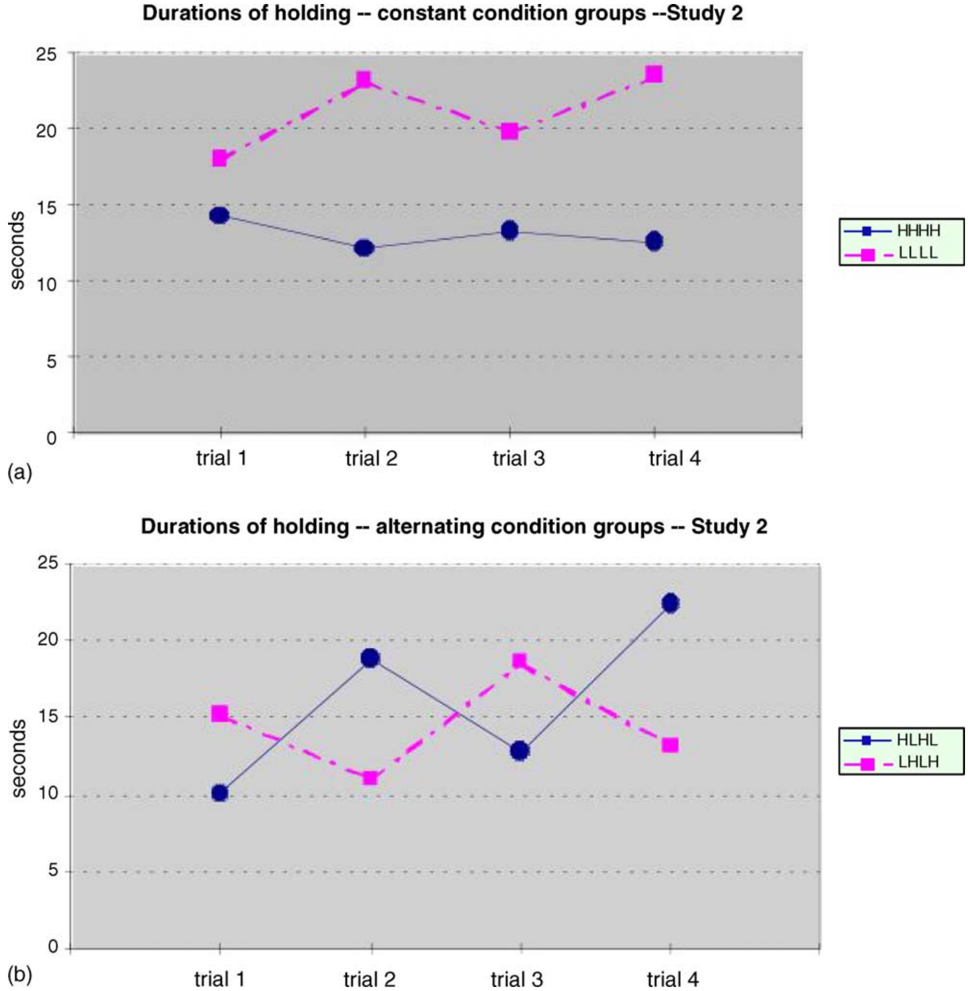

Fig. 5. The mean durations of holding on each trial for each stimulus group in Study 2. (a) The two constant condition groups. (b) The two alternating condition groups.

As the figure shows, infants given the light stimulus consistently held onto the object for longer durations than infants given the heavy stimulus did.

For the alternating condition, the secondary analysis yielded a significant first-stimulus × trials interaction $F(3,30) = 3.80$, $p = 0.02$. The mean durations for the two alternating stimulus groups and each trial are shown in Fig. 5b; as can be seen there, infants given the two stimuli alternately tended to hold the heavy stimulus for shorter durations than they held the light stimulus. To confirm this within-subject stimulus difference, the total duration holding the heavy stimulus (trials 1 and 3 for some infants, trials 2 and 4 for others) and the total duration holding the light stimulus (likewise trials 1 and 3 for some infants, trials 2 and 4 for others) were computed for each infant in the alternating condition. These durations were compared with a dependent samples *t*-test, which indicated that infants who experienced both stimuli held the heavy stimulus for shorter durations than they held the light stimulus, $t(11) = 3.183$, two-tailed $p = 0.009$.

Thus, the separate analyses of duration for the two conditions both reveal a sort of "preference" for the light stimulus in comparison to the heavy one. In the constant condition, there was a between-subjects difference: infants repeatedly given the light dumbbell held on to the stimulus for longer durations than infants repeatedly given the heavy dumbbell. In the alternating condition, there was a within-subjects difference: infants held the stimulus for longer durations on trials with the light dumbbell than on the trials with the heavy one. Moreover, the behavior of nine infants in the constant condition who completed more than four trials and thus were ultimately given the opposite-weight stimulus is also consistent with a preference for the light stimulus. All nine of these infants conformed to the pattern observed in the formal statistical analyses. Thus, if they had been holding the heavy stimulus throughout the first four trials ($n = 4$), they held the light stimulus ultimately presented on trial 5 or 6 for a longer duration than they had held the heavy stimulus on trial 4; conversely, if they had been holding the light stimulus throughout the first four trials ($n = 5$), they held the heavy stimulus ultimately presented on trial 5 or 6 for a shorter duration than they had held the light stimulus on trial 4.

Finally, the initial omnibus ANOVA for activity level yielded no significant effects or interactions. As in Study 1, the overall activity level for infants in the alternating condition ($M = 0.63$ crossings per second) was slightly higher than for infants in the constant condition ($M = 0.43$ crossings per second). However, this difference was not statistically significant, and furthermore it was evident on the first trial, so it is unlikely to represent a genuine condition effect.

3.3. Discussion

The results for Study 2 indicate that infants were able to discriminate the light and heavy stimuli. Infants given the light stimulus repeatedly held it for longer durations across all four trials than infants given the heavy stimulus repeatedly, and infants given the two stimuli on alternate trials likewise held the light stimulus for longer durations than the heavy one. Furthermore, infants given the two stimuli on alternate trials mouthed the stimuli to a greater extent than infants given the same stimulus over and over again, and they also increased their level of two-handed involvement with the stimuli over trials, whereas infants given the same stimulus repeatedly decreased theirs. Infants must have discriminated the stimuli based on their different weights, as the stimuli were identical in every other respect. Infants must also have discriminated the stimuli haptically, that is, with their hands and manual movements alone, as the stimuli were presented in the pitch dark and weight differences are not visible in any event.

The results of Study 2 provide the first evidence that infants as young as 3 months of age are sensitive to differences in weight. These results contrast with prior reports suggesting that infants do not perceive differences in weight until 8 or 9 months of age (cf., Itier et al., 2001; Mounoud & Bower, 1974; Palmer, 1989; Ruff, 1984). Likewise, in their analysis of infants' hand movements and haptic perception, Bushnell and Boudreau (1991, 1998) argued that weight perception should emerge at about 6 months, when infants first start to engage in cyclic waving and banging activities that approximate the hefting movements important for weight perception. Indeed, Bushnell and Boudreau invoked several attentional considerations to account for why weight perception seemed to be delayed relative to these enabling hand movements.

Two features of the procedure used here may explain why infants were able to respond to weight differences at an age so much younger than previously observed and hypothesized. First, the stimuli were presented in the pitch dark, so that only haptic properties were perceivable and infants' attention to them could not be diminished by attention to potentially more salient visual or bimodal properties. Earlier studies of infants' weight perception have all been conducted under normal lighting conditions, in which visible properties such as color, texture, and shape could have captured infants' attention to the point of precluding any awareness to the weight of the stimuli. Second, infants sat upright with their hands dangling freely at their sides in our procedure. Hence, once a stimulus was placed in the infant's hand, if he or she moved it in any way, the object was in effect being hefted against the force of gravity as is optimal for weight perception. In prior studies, infants have typically been seated at a table and had the option of gripping and inspecting the object while it rested on the surface, sliding it across the surface, and so on in addition to the more ideal (for weight perception) activity of lifting it from the surface. Thus, our positioning of the infants in a sense ensured that they would engage in activities important to weight perception, whether such young infants typically do or not, whereas the arrangements in prior studies left this more open and up to the infants themselves.

That infants were holding the stimuli in free space throughout the trials in our procedure raises the question of whether their differential responding was really subject-controlled. That is, it is possible that the heavy stimuli were consistently held for shorter durations because of a sort of biomechanical failure rather than because infants truly perceived the weights and actively preferred the lighter stimuli. The heavy stimuli may simply have strained the infants' muscles excessively and thus were literally "ripped from" their hands rather than deliberately let go. This account seems rather unlikely given that even the heavy stimuli weighed only 52 g and newborn infants can support their own weight of several thousand grams with the grasp reflex. Furthermore, the duration of holding the heavy stimulus did not decrease progressively over trials as one would expect if muscle strain or fatigue were an issue, and the difference between conditions for two-handed involvement emerged over trials, which implies a genuine perception, retention, and comparison of haptic information. Nevertheless, to explore the possibility that in Study 2, infants just could not hold onto the heavy stimulus any longer for purely physical (biomechanical) reasons, we conducted a third experiment as a control.

4. Study 3

In Study 3, an additional group of infants was tested with stimuli differing only in weight as in Study 2, but these infants were given the stimuli under normal lighting conditions rather than in the pitch dark. Our reasoning was that if the shorter duration of holding the heavy stimulus in Study 2 was due to the sheer physical strain it imposed, then this factor would operate under normal lighting conditions as well and infants in Study 3 should likewise hold the heavy stimulus for shorter durations than the light one. However, if the results of Study 2 reflect genuine perception of weight with a preference for the lighter stimulus, this effect might be mitigated under normal lighting when visible aspects of the stimuli could occupy infants' attention, as outlined by Bushnell and Boudreau (1991, 1998). In this event, infants in Study 3 would be expected to perform like young infants in previous reports in the literature and provide no evidence for discriminating weight differences.

4.1. Method

4.1.1. Participants

Sixteen 3-month-old infants ($M = 2$ mos, 28.75 dys; range = 2 mos, 17 dys to 3 mos, 11 dys), seven males and nine females, were included in the final sample. Five additional infants were also tested but not included in the final sample, one because of experimenter error, one because of parental interference, and three because they refused to hold the stimulus objects or became fussy before completing at least four trials. The infants were recruited by telephone solicitation from a subject pool consisting of infants born in the greater Atlanta area. Participating infants were predominantly from white, middle-class families, and all were healthy and born full-term (greater than 38 weeks gestational age and with a birth weight of 2500 g or more) according to parental reports. Infants were tested individually in a university laboratory in the presence of a parent, who had provided informed written consent. None of the infants participating in Study 3 had previously participated in Study 1 or Study 2.

4.1.2. Stimuli, physical arrangement, and equipment

The stimuli were the same heavy and light dumbbell objects as were used in Study 2. The physical arrangement and equipment used were similar to those for Studies 1 and 2, except that test sessions for Study 3 were conducted and recorded with the ordinary room lights on rather than in the dark with infrared lighting and video equipment. As in the earlier studies, infants sat upright straddling a parent's knee, and parents were instructed to provide only postural support for their infants and otherwise to remain still, silent, and non-interactive during the session. Parents and infants sat facing a blank white wall, and the infant's behavior was recorded with a zoom-lens camcorder (Panasonic model AG-186) set some distance away and slightly to the infant's right. The video signal was also fed through to a TV monitor (Panasonic model CR-1382) placed on the floor behind the infant for on-line viewing.

4.1.3. Procedure and design

The procedure and design were essentially identical to those used for Study 2, except that the room lights remained on throughout. An experimenter positioned behind the infant placed each stimulus in the infant's right hand in the same manner as for Studies 1 and 2. A second experimenter also positioned behind the infant watched the trial on the TV monitor and initiated a stopwatch as soon as the infant was gripping the stimulus independently. If the infant dropped the stimulus without holding it for at least 3 s, the same stimulus was given to the infant again and the trial restarted. Once the infant had held the stimulus for this minimum time, he or she was permitted to explore it freely until it was dropped or until 25 s had passed, at which point the next stimulus in the series was presented. As in Study 2, infants were presented the heavy and light stimuli in one of four predetermined sequences. Infants in the constant condition were presented four successive trials with the heavy (HHHH) or four successive trials with the light (LLLL) stimulus. Infants in the alternating condition received four alternating trials with the heavy and light stimuli, starting with either the heavy stimulus (HLHL) or the light stimulus (LHLH) first. Four infants were tested with each of the four sequences. There were two males and two females presented with each sequence, except that for the LLLL sequence there was one male and three females. The original design called for each infant to also be presented with four more trials in the opposite condition following the completion of the first four trials. However, only about half of the infants completed all eight planned trials, so the principal analyses were conducted on just the first four trials.

4.1.4. Measures and scoring

The video records for each infant's completed trials were scored for the same four measures as in Studies 1 and 2, that is, duration of holding, mouthing, two-handed involvement, and activity level. These were scored in the same manner and with the same criteria and body-scaled grids as before. Each trial for each infant was scored by two observers working independently. The average of the two observers' scores for each measure was used in the statistical analyses.

4.2. Results

The scores for each of the four measures were subjected to a condition (constant versus alternating) by first-stimulus (heavy versus light) by trials Analysis of Variance. The analysis for mouthing yielded no significant main effects or interactions. The overall level of mouthing in Study 3 (grand mean = 0.59 on the 0–2 scale) was somewhat higher than with the same stimuli in Study 2 (grand mean = 0.42), but as in the earlier studies, mouthing was generally relatively rare and mainly a matter of individual differences. In each condition and with each stimulus, there were particular infants who never mouthed at all and others who mouthed on every trial.

The omnibus ANOVA for two-handed involvement also yielded no significant main effects or interactions. On average, two-handed involvement was even rarer in Study 3 (grand mean = 0.23 on the 0–2 scale) than with the same stimuli in Study 2 (grand mean = 0.32). Only five infants of the 16 infants engaged in this behavior at all, two in the LHLH sequence and one in each of the others.

The initial analysis of durations yielded a significant condition effect, $F(1,12) = 6.97$, $p = 0.022$, a significant first-stimulus effect, $F(1,12) = 6.39$, $p = 0.027$, and a condition × first-stimulus interaction, $F(1,12) = 7.67$, $p = 0.017$. There were no other significant main effects or interactions. To explore these results further, separate first-stimulus × trials analyses of variance were conducted for the two conditions. For the constant condition, this secondary analysis yielded a main effect of first-stimulus, $F(1,6) = 10.00$, $p = 0.019$, and a significant trials effect, $F(3,18) = 3.20$, $p = 0.048$. The mean durations for the two constant stimulus groups and each trial are shown in Fig. 6a. As the figure shows, infants given either stimulus repeatedly tended to hold the stimulus for shorter durations on the first trial than on the subsequent trials. The figure also shows that infants given the heavy stimulus consistently held onto the object for longer durations than infants given the light stimulus did. Note that this difference is opposite from the apparent preference for the light stimulus exhibited by infants in Study 2.

For the alternating condition, the secondary analysis yielded no significant main effects or interactions. The mean durations for the two alternating stimulus groups and each trial are shown in Fig. 6b; as can be seen there, infants given the two stimuli alternately did not systematically favor one stimulus over the other. If anything, they tended to hold the heavy stimulus for shorter durations than they held the light stimulus, in contrast to infants in the constant condition.

Thus, the separate analyses of duration for the two conditions in Study 3 are not consistent with one another as to whether infants preferred one stimulus over the other. In the constant condition, there was a between-subjects difference: infants repeatedly given the heavy dumbbell held on to the stimulus for longer durations than infants repeatedly given the light dumbbell. In the alternating condition, however, there was not a corresponding within-subjects difference: infants held the stimulus for similar durations on trials with the heavy dumbbell as on trials with the light one. What's more, all eight infants in the constant condition completed more than four trials and thus were ultimately given at least one trial with the opposite-weight stimulus. Of these, only three conformed to a preference for the heavy stimulus as suggested by the between-subjects analysis of their first four trials. One other showed the opposite pattern, holding the heavy stimulus for a shorter duration than she had previously held the light one, and four of these infants held the opposite-weight stimulus for an equal length of time – in fact for the maximum of 25 s – as they had most recently held the one they were initially given.

In general, infants in Study 3 held on to the stimuli for longer durations (grand mean = 20.66 s) than infants did with the same stimuli in Study 2 (grand mean = 16.21 s). Indeed, 7 of the 16 infants in Study

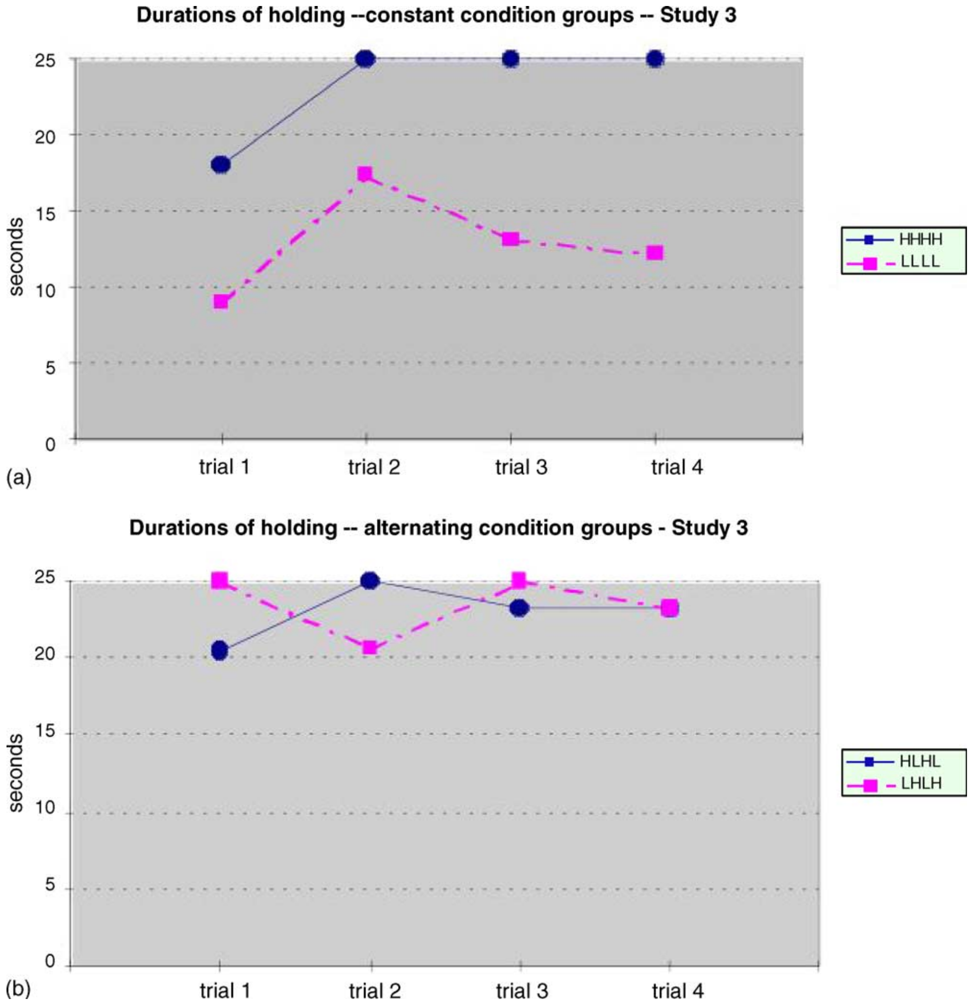

Fig. 6. The mean durations of holding on each trial for each stimulus group in Study 3. (a) The two constant condition groups. (b) The two alternating condition groups.

3 held on to the stimulus for the maximum of 25 s on every one of their first four trials, whereas only 3 of the 24 infants in Study 2 did so. Interestingly, the three infants in Study 2 had all been presented the LLLL sequence, whereas none of the seven prolonged holders in Study 3 had been presented the LLLL sequence.

Finally, the analysis on activity level yielded a marginally significant conditions effect, $F(1,12) = 3.71$, $p = 0.078$, and no other significant effects or interactions. Infants in the constant condition ($M = 0.517$) were somewhat more active than infants in the alternating condition ($M = 0.278$). However, this was the case even on the first trial, so the difference is unlikely to represent a genuine condition effect. Note too that the activity level difference in Study 3 is in the opposite direction to the likewise suspect trend with the same stimuli in Study 2.

4.3. Discussion

The results for Study 3 provide only rather weak evidence that infants were able to discriminate the light and heavy stimuli. Infants did not mouth the heavy and light stimuli differentially nor did they involve the second hand differentially in their explorations of them. Although infants given the same stimulus over and over again were somewhat more active than infants given the heavy and light stimuli alternately, this was true even before any alternations had occurred and thus probably reflects coincidental individual differences. The only real suggestion that infants discriminated the stimuli is that among the infants given the same stimulus repeatedly, those given the heavy stimulus held it for longer durations than infants given the light stimulus held it. However, this difference was not paralled by a similar difference across trials among the infants given the two stimuli alternately, and furthermore, when infants given the same stimulus repeatedly were ultimately given the opposite stimulus, they did not exhibit a preference for the heavy stimulus.

The failure of 3-month-old infants to exhibit robust weight discrimination in Study 3 is consistent with prior research on weight perception. Both Mounoud and Bower (1974) and Palmer (1989) found that while 9-month-olds exhibited different manual behaviors with heavy versus light objects, 6-month-olds did not, and Ruff (1984) observed that neither 9- nor 12-month-old infants responded in any special way to an object changed in weight from one they had previously explored. Itier et al. (2001) found that 8-, 11-, and 14-month-olds preferentially manipulated a heavy object amongst several lighter ones; however, they did not test any younger infants. These previous studies were all conducted under normal lighting conditions, as was Study 3. Thus when the stimulus objects themselves as well as other things in the room are visible, infants 6 months of age and younger do not seem to be sensitive to differences in the weight of objects they handle. This contrasts with the results of Study 2, in which young infants tested in the pitch dark responded differently to heavy and light stimuli on several behavioral measures. The apparent role of visibility in weight perception will be discussed in the Section 5 below.

Finally, the results of Study 3 establish that the heavy stimuli used in Studies 2 and 3 are not so heavy that young infants simply cannot hold onto them for sustained periods of time. As Fig. 6a and b show, infants held onto the heavy stimulus for the full duration or nearly the full duration of almost every trial, and they did not fatigue and show decreasing durations of holding over trials with the heavy stimulus. Furthermore, infants in Study 3 held onto the heavy stimulus for between 4 and as much as 13 s longer per trial than did infants in the corresponding trials and conditions of Study 2 (compare Fig. 6a and b to Fig. 5a and b). These results clarify that the results of Study 2 cannot be accounted for by limitations in the physical strength of young babies. The infants in Study 2 presumably were as strong as the same-aged infants in Study 3 and thus had the strength to hold onto the heavy stimuli for longer durations than they did. Something other than biomechanical failure, as it were, must be responsible for why they held the heavy and light stimuli for different durations.

5. General Discussion

The results of Study 1 indicate that under appropriate conditions, 3-month-old infants can haptically perceive material properties in general, and likewise the results of Study 2 indicate that they can haptically perceive the object property of weight in particular. In both studies, infants' differential responding to the distinct stimuli included across-trials effects in addition to differences present on the initial trials.

Thus infants must have actually perceived and remembered the stimulus qualities here, rather than just accommodated their grasps differentially to them as was possible in prior research on early sensitivity to hardness (Rochat, 1987) and texture (Molina & Jouen, 1998). Furthermore, the various dumbbell stimuli presented here had to be gripped all in the same fashion, so infants' differential responding could not have been based on memory for different hand postures as was possible in many prior studies of early haptic perception (cf., Streri & Milhet, 1988; Streri & Spelke, 1988, 1989). Thus, the results reported here represent evidence for genuine haptic perception of material properties at an earlier age than has been previously documented.

That infants in Study 2 discriminated stimuli different only in weight raises a question about the basis of infants' performance in Study 1, where the stimuli were different in multiple material properties including in weight. Was infants' differential responding in Study 1 predicated on only on the weight difference between the stimuli, or did the temperature, texture, and compliance differences also contribute to their differential responses? In support of the former, it can be noted that the apparent preference for the curler stimulus in Study 1 parallels the apparent preference for the light stimulus in Study 2, as the curler stimulus was lighter by some 18 g than the spring stimulus. However, other patterns of responses in the two studies were different—there was a significant effect for activity level in Study 1 but not in Study 2, and there were significant effects for mouthing and two-handed involvement in Study 2 but not in Study 1. These differences could have been related to the additional material properties varying between the stimuli in Study 1 or to the greater weight difference between the stimuli in Study 2. In order to clarify what underlies the similar but not identical patterns of results for Studies 1 and 2, further research with stimuli differing only in temperature, only in texture, and only in compliance should be conducted. Nevertheless, despite this remaining ambiguity, it is important to reiterate that the results reported here represent the first evidence for haptic perception of material properties in general and of weight in particular by infants as young as 3 months of age.

The results reported here also reveal some important limitations of early haptic perception, though. First, it is noteworthy that although infants perceived and discriminated the stimuli, they did not explore them with hand movements specific to the properties in question. That is, they did not explore the different textures with stroking movements, the different compliances with pressing or squeezing, the different weights with hefting, and so on, as Lederman and Klatzky (1987) observed adults to do. Instead, infants responded to the stimuli and to changes of stimuli with different extents of generic exploratory behaviors such as holding on versus letting go of the stimulus, mouthing it, and arousal or waving it around in space with arm and shoulder movements. These responses may reflect young infants' inability to deliberately move the fingers independently and precisely, and they suggest that young infants may encode haptic stimuli in very general terms, as simply "different" from the last or as "pleasant versus unpleasant". Lewkowicz (1991) has likewise suggested that very young infants perceive visual and auditory stimuli along a single dimension of overall intensity, rather than in terms of various separable dimensions such as color, shape, tone, rhythm, etc. At any rate, because of the generic nature of their interactions with the stimuli, it seems likely that young infants do not experience these stimuli in the same way as adults or even older infants capable of more precise finger movements would experience them. Their differentiating the stimuli is probably dependent on different patterns or extents of responding by cutaneous and stretch receptors in static contact with the stimuli, as Streri et al. (2000) described in their study of newborns' haptic perception of a curvilinear versus rectilinear edge. This interpretation in turn implies that young infants might be unable to discriminate stimuli whose haptic differentiation required encoding dynamic receptor patterns or integrating information across time (as in contour following to perceive configurational shape, e.g.).

Another limitation on young infants' haptic perception is revealed by a comparison of the results of Studies 2 and 3. The stimuli and procedures for these two studies were identical except that Study 2 was conducted in the dark and Study 3 under normal room lighting; in Study 2, infants evidenced weight perception in both conditions and on several variables, while in Study 3, there was only limited evidence for weight perception in one condition and on one variable. This contrast dispels any concern that infants' exploration was compromised by being tested in the dark. Although the drop-out rates were slightly higher for Studies 1 and 2 in the dark than for Study 3 in the light, it seems that weight perception was actually facilitated and perhaps only possible in the dark! Similarly, both Stack and Tsonis (1999) and Bushnell, Boudreau, Weinberger, and Roder (1992) found that infants more effectively explored and discriminated different textures when the stimuli were not visible as compared to when they were visible. Infants' haptic abilities evidently operate best when they touch objects without seeing them at the same time, as though seeing them somehow detracts from feeling them. Bushnell and Boudreau (1991) anticipated this kind of divided attention effect in speculating about why weight perception (in the light) emerged later in development than infants' motor abilities would predict. They suggested that bimodal properties such as shape, size, and 3-D structure may command infants' attention in the light, leaving little or no resources to process solely haptic properties such as weight. Boudreau and Bushnell (2000) empirically documented a similar "trade-off" between cognitive processing and the motor demands of tasks for infants. Their results together with the dark/light contrasts discussed here highlight the fact that competition for attention is a real process and can be an important determinant of infant behavior. The dark/light contrasts discussed here also suggest that in future research on young infants' haptic abilities, stimuli might best be presented in the dark or some other invisible condition. Later in development, when processing capacities improve and various objects and object properties are more familiar, perceiving haptic properties can presumably occur concurrently with perceiving bimodal properties and is thus not obscured under normal lighting.

Finally, the results reported here in contrast with results of prior research highlight the fact that developmental abilities are contextually sensitive. Infants in Study 2 evidenced robust discrimination of weight, whereas earlier findings indicated that infants do not perceive weight until 8 or 9 months of age (cf., Itier et al., 2001; Mounoud & Bower, 1974; Palmer, 1989; Ruff, 1984). In addition to the light/dark difference already discussed, infants in our research were held sitting vertically in open space while infants in prior studies were seated in either a reclining position or at a table. This postural difference meant that infants in Study 2 were basically guaranteed to feel the pull of gravity on the object whereas in prior research the object might be supported against gravity by resting on the infant's chest or on the tabletop. This contrast implies that under everyday circumstances, infants might not have ample opportunities to perceive weight until they are capable of sitting by themselves. Thus postural limitations may ordinarily constrain young infants' ability to perceive weight, and this "latent" ability may only be revealed when infants are artificially supported in postures they cannot achieve on their own. Similarly, (Rochat (1992); Rochat & Goubet, 1995; Rochat, Goubet, & Senders, 1999) has shown how postural differences and abilities may influence infants' reaching abilities and styles, and Rochat and Bullinger (1994) discussed how posture and functional action in general interact uniquely during infancy. Bushnell and Boudreau (1993) likewise outlined how various perceptual abilities might be exhibited "before their time" if motor abilities not typically present at a given age are simulated or provided by experimenters. These considerations, possibly embodied by the early perception of weight shown in the present research, reinforce the important concept of scaffolding in development, and they simultaneously serve as a caution that singular abilities documented empirically must always be interpreted in light of the context in which they are observed.

Acknowledgements

We would like to thank Beth Rosenblatt for "inventing" the dumbbell stimuli used in all the studies and Philip Rochat for the use of his equipment and laboratory at Emory University for conducting Study 3. We would also like to thank Keri Adams, Adam Gardner, Monica Gill, Angela Pearce, Sarah Ulanet, Jane Yang, and Layne Zwick for the help in testing infants and scoring videotapes. Finally, we extend our gratitude and best wishes to the families whose infants participated in the research reported here.

References

Boudreau, J. P., & Bushnell, E. W. (2000). Spilling thoughts: configuring attentional resources in infants' goal-directed actions. *Infant behavior and Development*, *23*, 543–566.

Brown, K. W., & Gottfried, A. W. (1986). Cross-modal transfer of shape in early infancy: is there reliable evidence? In L. P. Lipsitt & C. Rovee-Collier (Eds.), *Advances in infancy research: vol. 4* (pp. 163–170). Norwood, NJ: Ablex.

Bushnell, E. W. (1985). The decline of visually guided reaching during infancy. *Infant Behavior and Development*, *8*, 139–155.

Bushnell, E. W., & Boudreau, J. P. (1991). The development of haptic perception during infancy. In M. A. Heller & W. Schiff (Eds.), *The Psychology of touch*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Bushnell, E. W., & Boudreau, J. P. (1993). Motor development and the mind: the potential role of motor abilities as a determinant of aspects of perceptual development. *Child Development*, *64*, 1005–1021.

Bushnell, E. W., & Boudreau, J. P. (1998). Exploring and exploiting objects with the hands during infancy. In K. Connolly (Ed.), *The Psychobiology of the hand* (pp. 144–161). Cambridge, UK: Mac Keith Press.

Bushnell, E. W., Boudreau, J. P., Roder, B. J., & Weinberger, N. (May 1992). Groping in the dark: infants' haptic exploration with and without vision. In *Poster presented at the International Conference on Infant Studies*.

Bushnell, E. W., & Weinberger, N. (1987). Infants' detection of visual-tactual discrepancies: Asymmetries that indicate a directive role of visual information. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 601–608.

Fagard, J. (1998). Changes in grasping skills and the emergence of bimanual coordination during the first year of life. In K. Connolly (Ed.), *The Psychobiology of the hand* (pp. 123–143). Cambridge, UK: MacKeith Press.

Gordon, A. M., Forssberg, H., Johansson, R. S., & Westling, G. (1991). The intgration of haptically acquired size information in the programming of precision grip. *Experimental Brain Research*, *83*, 483–488.

von Hofsten, C., & Siddiqui, A. (1993). Using the mother's actions as a reference for object exploration in 6- and 12-month-old infants. *British Journal of Developmental Psychology*, *11*, 61–74.

Itier, R. J., Provasi, J., & Bloch, H. (2001). Integration of the property of weight into infants' manipulation. *Current Psychology Letters: Behavior, Brain, and Cognition*, *4*, 51–65.

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, *56*, 550–564.

Johansson, R. S., & Westling, G. (1987). Signals in tactile afferents from the fingers elicting adaptive motor responses during precision grip. *Experimental Brain Research*, *66*, 141–154.

Johansson, R. S., & Westling, G. (1988). Programmed and triggered actions to rapid load changes during precision grip. *Experimental Brain Research*, *71*, 72–86.

Kellog, W. N., & Kellog, L. A. (1933). *The ape and the child*. New York: McGraw-Hill.

Klatzky, R. L., & Lederman, S. J. (1993). Toward a computational model of constraint-driven exploration and haptic object recognition. *Perception*, *22*, 597–621.

Klatzky, R. L., & Lederman, S. J. (1995). Identifying objects from a haptic glance. *Perception and Psychophysics*, *57*, 1111–1123.

Klatzky, R. L., Lederman, S. J., & Metzger, V. A. (1985). Identifying objects by touch: an "expert system". *Perception and Psychophysics*, *37*, 299–302.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: the salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General*, *116*, 356–369.

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: a window into haptic object recognition. *Cognitive Psychology*, *19*, 342–368.

Lederman, S. J., & Klatzky, R. L. (1990). Haptic object classification: knowledge-driven exploration. *Cognitive Psychology*, *22*, 421–459.

Lewkowicz, D.J. (1991). Development of intersensory functions in human infancy: Auditory/visual interactions. In: M. J. S., Weiss, & P. R., Zelazo (Eds.), *Newborn attention: Biological constraints and the influence of experience* (pp. 308–338).

Lockman, J. J., & McHale, J. P. (1989). Object manipulation in infancy: developmental and contextual determinants. In J. J. Lockman & N. L. Hazen (Eds.), *Action in social context: Perspectives on early development* (pp. 129–167). New York: Plenum.

Molina, M., & Jouen, F. (1998). Modulation of the palmar grasp behavior in neonates according to texture property. *Infant Behavior and Development*, *21*, 659–667.

Mounoud, P., & Bower, T. G. R. (1974). Conservation of weight in infants. *Cognition*, *3*, 29–40.

Palmer, C. F. (1989). The discriminating nature of infants' exploratory actions. *Developmental Psychology*, *25*, 885–893.

Pineau, A., & Streri, A. (1990). Intermodal transfer of spatial arrangement of the component parts of an object in infants aged 4–5 months. *Perception*, *19*, 795–804.

Rochat, P. (1987). Mouthing and grasping in neonates: evidence for the early detection of what hard or soft substances afford for action. *Infant Behavior and Development*, *10*, 435–449.

Rochat, P. (1989). Object manipulation and exploration in 2- to 5-month-old infants. *Developmental Psychology*, *25*, 871–884.

Rochat, P. (1992). Self-sitting and reaching in 5- to 8-month-old infants: The impact of posture and its development on early eyeand coordination. *Journal of Motor Behavior*, *24*, 210–220.

Rochat, P., Bullinger, A., (1994). Posture and functional action in infancy. In A., Vyt, H., Bloch (Eds.), *Early child development in the French tradition: Contributions from current research* (pp. 15–34).

Rochat, P., & Goubet, N. (1995). Development of sitting and reaching in 5- to 6- month-old infants. *Infant Behavior and Development*, *18*, 53–68.

Rochat, P., Goubet, N., & Senders, S. J. (1999). To reach or not to be reach? Perception of body effectivities by young infants. *Infant and Child Development*, *8*, 129–148.

Ruff, H. A. (1984). Infants' manipulative exploration of objects: effects of age and object characteristics. *Developmental Psychology*, *20*, 9–20.

Santello, M., Flanders, M., & Soechting, J. F. (1998). Postural hand synergies for tool use. *Journal of Neuroscience*, *18*, 10105–10115.

Stack, D. M., & Tsonis, M. (1999). Infants' haptic perception of texture in the presence and absence of visual cues. *British Journal of Developmental Psychology*, *17*, 97–110.

Streri, A. (1987). Tactile discrimination of shape and intermodal transfer in 2- to 3-month-old infants. *British Journal of Developmental Psychology*, *5*, 213–220.

Streri, A., Lhote, M., & Dutilleul, S. (2000). Haptic perception in newborns. *Developmental Science*, *3*, 319–327.

Streri, A., & Milhet, S. (1988). Intermodal transfer in object's shape between vision and touch in 2-month-old infants. *Annee Psychologique*, *88*, 329–341.

Streri, A., & Pecheux, M. (1986). Vision-to-touch and touch-to-vision transfer of form in 5-month-old infants. *British Journal of Developmental Psychology*, *4*, 161–167.

Streri, A., & Spelke, E. S. (1988). Haptic perception of objects in infancy. *Cognitive Psychology*, *20*, 1–23.

Streri, A., & Spelke, E. S. (1989). Effects of motion and figural goodness on haptic object perception in infancy. *Child Development*, *60*, 1111–1125.

Streri, A., Spelke, E., & Rameix, E. (1993). Modality-specific and amodal aspects of object perception in infancy: the case of active touch. *Cognition*, *47*, 251–279.

Thelen, E. (1979). Rhythmical stereotypies in normal human infants. *Animal Behaviour*, *27*, 699–715.

Thelen, E. (1981). Rhythmical behavior in infancy: an ethological perspective. *Developmental Psychology*, *17*, 237–257.

Vauclair, J. (1984). Phylogenetic approach to object manipulation in human and ape infants. *Human Development*, *27*, 321–328.