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Motor constraints on the development of perception-action matching in infant reaching

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Abstract

Previous studies on reaching and grasping have suggested that infants need considerable experience at both seeing and touching in order to develop responses adapted to the environment. Such an account, however, does not reveal how appropriate perception-action matching emerges from these repeated experiences at seeing and touching. The present research addresses this issue by investigating the dynamics of perceiving and acting in 5- to 9-month-old infants as they saw, reached for, touched, and grasped objects of different sizes and texture. To gain insights into the mechanisms of change that underlie pattern formation, we observed infants' responses as a function of time, as infants reached for and manipulated objects successively. We found that the developmental process by which appropriate perception-action matching emerges is tied to important changes in the motor system. Before 8 months, infants' reaching responses are constrained by systemic motor tendencies that conflict with the process of perceptual-motor mapping. When these motor tendencies disappear, infants are able to use and integrate visual and haptic information to scale their actions to objects. These results are consistent with a dynamic systems approach, which views behavioral changes and their underlying psychological processes as the product of continuous tensions and interactions between the organism's own constraints and the characteristics of the task at hand. © 2000 Elsevier Science Inc. All rights reserved.

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1. Introduction

The physical properties of objects – their appearance but also their feel – play an important role in shaping our actions (Bushnell & Boudreau, 1993; Newell et al., 1989; Ruff, 1984). Imagine, for example, that you need to move a large object, say, a cooler equipped with two handles. Based on its size, you first decide to reach for it with two hands, but as you lift it and discover that it is empty and lightweight you decide to release one handle, so you can use that freed hand to grab something else on your way. Now reverse the scenario: Imagine that you are grabbing a small flowerpot with one hand. As you lift it and realize that it tilts dangerously, you decide to use your second hand in order to straighten the pot and move it safely to another location.

It is through perceptual-motor experiences like these, involving seeing, reaching, touching, and grasping, that we continually improve and update our understanding and knowledge of the environment. Not only do we discover the physical properties of our environment as we act upon it and perceive it, but we also use these discovered properties to modify, anticipate, and organize future actions as similar situations reappear. Imagine, for example, that you need to move the cooler and the flowerpot again. The second time you reach for these objects you will use different action patterns than the first time, because as you manipulated these objects once, you remembered their respective weights, and now plan to use one hand for the cooler and two hands for the flower pot despite their sizes.

Adults and children, who are experts at manipulating objects, rely on their visual and haptic perception all the time in order to plan, scale, and adjust their actions effectively to their environment (Newell et al., 1989; Cesari & Newell, 2000). However, because adults and children have had long experience at manipulating a wide variety of objects in many situations, they can accurately plan most of their actions based on visual information only. They do not necessarily need additional haptic information to make appropriate action decisions. For instance, they know, without using touch, that a large and soft pillow can be grabbed with one hand, and that a beach ball requires two hands despite its light weight. Only a few situations, like the ones illustrated above, will need haptic information to make appropriate action decisions.

What do we know about infants who are not as experienced as adults and children? Are they capable of using their sight and touch effectively to adapt their reach and grip configurations to objects' physical properties? Previous research on this topic provided two seemingly contradictory results. On the one hand, studies that focused on the transport portion of the reach – that is, the movements performed prior to the hand contacting the object – found that infants begin to plan their motor response effectively as a function of objects' physical properties around 8 months old. For example, several studies reported that 8-month-old infants can anticipate the shape and orientation of objects before they actually touch and grasp them. That is, they preshape their hand grip configuration while their arms are still moving toward the object (Von Hofsten & Fazel-Zandy, 1984; Von Hofsten & Rönnqvist, 1988; Lockman et al., 1984; Piéraut-Le Bonniec, 1985). Moreover, at around the same age, infants begin to use either one or two arms appropriately to reach for small or large objects (Fagard & Pezé, 1997). Like adults, they extend both hands forward for a beach ball, and one hand for a marble.

Other studies, on the other hand, that centered more specifically on the grip configuration following contact with the target found much more precocious abilities. Three studies reported that infants as young as 4 or 5 months old are already capable of adjusting their grip configuration to object size. Not only are infants able to adapt the appropriate number of fingers to various object sizes, but they also seem to be able to determine when they need to use one or two hands to grasp small or large objects (Newell et al., 1989; Newell et al., 1993; Siddiqui, 1995).

According to Newell et al. (1989), these developmental discrepancies between reaching and grasping skills are due to the differing types of sensory information that infants use between 4 and 8 months old. In their study, Newell et al. (1989) reported that the youngest infants – the 4- to 6-month-olds – adjusted their grip configurations to the properties of the objects only after they had contacted it. Thus, they concluded that young infants needed to rely on haptic information in addition to visual information to effectively scale their grip to object size. The 7- and 8-month-old infants, in contrast, did not necessarily require haptic information to adjust their grip configuration. Similarly to adults and children, they could shape their hand configuration before contact using mainly visual information. Clearly, this is a more sophisticated strategy, allowing infants to reach correctly on their very first reach, without a period of post hoc calibration.

This research, however, leaves one question unanswered. If young infants can use haptic information to adjust their grip configuration to object size as early as 4 months old, why don't they take advantage of that perceptual-motor experience right away to refine and organize their response like 8-month-olds would do, or like the adults and children would do in the cooler and flowerpot examples that we introduced earlier? Why do infants wait until 8 months old to be able to organize their responses ahead of time, without relying on haptic information? Because previous infant research studied reaching and grasping responses separately, little is known about the developmental process by which increasingly efficient perception-action matching emerges between 4 and 8 months old.

Indeed, we see a problem with the account that change in behavior between 4 and 8 is mainly depending on the use of differing types of sensory information (Newell et al., 1989). Such a developmental account implies a straightforward case of gradual perceptual learning, where infants' discovery of how to adapt their responses to objects' physical properties is entirely guided by their repeated perceptual experiences at touching and seeing. The problem with this developmental scenario is that it stresses only the perceptual side of this developmental process without acknowledging developmental changes that might occur on the action side. Stressing changes in the perception side only supposes that infants already have a full range of movements available that they can use and modify according to the changing environment, and that these motor abilities – needed for reaching and manipulation – would be ready, from the onset, to subserve information provided by the different perceptual modalities. Such suppositions might not be warranted.

The aim of the present research is to investigate the dynamics of perceiving and acting in 5- to 9-month-old infants as they see, reach for, touch and grasp objects of different sizes and texture. To gain insights into the mechanisms of change that underlie pattern formation, we observed infants' responses as a function of time following two time scales: the *shorter time scale,* as infants saw, reached, touched and grasped objects trial after trial, and the *larger* *developmental time scale,* as infants of different ages responded to these repeated acts of seeing, reaching, touching, and grasping. Our goals were twofold: (1) to focus on the movement patterns performed prior to and after contact with the object in order to infer from the observed responses whether infants use different perceptual modalities (vision and/or touch) to reach for and grasp objects of different size and texture, and (2), to assess from successive responses whether infants between 5 and 9 are capable of remembering and integrating perceptual-motor experiences from previous reaches and object manipulations to adapt to the changing characteristics of the task.

We show that infants' ability to learn from and adapt to their perceived environment is tightly linked to their ability to control and modulate their arm and hand coordination. More specifically, we show that before 8 months old, infants cannot fully adapt their responses to the perceived properties of objects because they have not developed the movement flexibility to do so. Unlike adults and children who have a full range of movements available to match varied perceptual information, young infants' reaching responses might be temporarily constrained by much more limited motor capabilities.

1.1. Motor constraints, the development of reaching, and perception-action matching

In classic studies, researchers believed that learning to reach involved primarily perceptual processes: matching the sight of the object with the feel of the hand and arm (Piaget, 1952; White et al., 1964). However, recent research has called attention to the specific motor aspects of the task. In particular, recent work has shown that infants are faced with important motor constraints to overcome when learning to reach, and that these motor problems need to be solved before infants can successfully make the needed perceptual matches. For example, in their longitudinal study on the development of infant reaching, Thelen and collaborators identified biomechanical constraints on developing arm control (Thelen et al., 1993; Thelen et al., 1996). They found that intrinsic biomechanical forces directly arising from infants' self-generated arm movements acted as perturbations on infants' arm trajectories and tended to drag their arm away from the intended goal. Although infants were able to see and locate the wanted target, vision of the toy alone did not suffice to guide the movement directly to its goal. Infants also had to learn how to master these intrinsic biomechanical forces by calibrating muscle activity and movement speed to the task demands.

In further extensions of this study, these authors demonstrated that these motor constraints also interacted with infants' initial capabilities to adapt certain objects' physical properties. Corbetta and Thelen (1994), for instance, observed that the early intrinsic biomechanical forces generated during the reach, tended to irradiate to the other arm, triggering bimanual responses in reaching, although the objects used in their study were always small, one-handed objects. Moreover, Corbetta and Thelen (1994, 1996) found that these early tendencies to reach bimanually persisted for several weeks after the onset of reaching, and did so despite the fact that infants were repeatedly allowed to touch and mouth the toys after grabbing them. In this case, active haptic exploration of the objects did not seem to alter infants' initial tendencies to reach bimanually for small objects. Here again, these authors found that important motor constraints, namely the tendency to reach with two arms, interfered with infants' capability to develop differentiated reaching responses adapted to object size.

Finally, Thelen and collaborators observed that these early motor constraints dissipated around 30–36 weeks old (Corbetta & Thelen, 1994, 1996; Thelen et al., 1996). At that time, infants produced smoother, straighter, and more stable reaching trajectories, and some infants developed more lateralized, unimanual tendencies for reaching for small objects. This change in behavior matched the age at which infants usually begin to effectively anticipate and preshape their reaching response to objects' physical properties (Fagard & Pezé, 1997; Lockman et al., 1984; Von Hofsten & Fazel-Zandy, 1984).

Together, these data suggest that initially infants do not have a full range of movements available to match to the properties of objects. Rather, they indicate that early motor constraints may temporarily supersede perceptual information. Only when these constraints are overcome can infants fully benefit from experience to learn perception-action matches. However, because these previous studies did not fully investigate how motor constraints interacted with infants' perceptual abilities when confronted to a changing environment, such developmental progression still needs to be demonstrated.

In this study, we paid particular attention to infants' initial tendencies to reach for objects with one or two hands. We investigated whether similar pervasive motor constraints interacted with infants' ability (1) to adjust their one- or two-handed reaching patterns to objects of different size and texture, and (2) to use previous one- or two-handed object manipulation to increase their action-environment match. The assumption for adults is that one- and two-handed reaching are equally available and the choice depends only on the perceptual information – visual and/or haptic. In infants, however, because our previous work has suggested that both coordinative patterns, one- and two-handed responses, may not be equally accessible, infants may not vary their motor response and consistently reach for and manipulate perceptually different objects with the same pattern (Corbetta & Thelen, 1996). Thus, infants may use an inappropriate response, not because of faulty perceptual judgment, but because a motor pattern may be so strong that it cannot be modified.

To address these two issues, we tested the reaching and grasping abilities of 5- to 9-month-old infants with two series of objects of varying sizes – one solid and one soft. The solid object series required one- or two-handed responses to reach for and grasp them depending on their size. Thus, infants who can make accurate decisions for action based on object size and have motor flexibility should use different one- and two-handed patterns to reach for them. The soft object series, on the contrary, always offered the option to use one hand to reach for and grasp objects regardless of their size. This situation is comparable to adults' reaching for a large pillow. In this situation, if infants can take advantage of previous object manipulations, they should be able to modify their response and reach for the next large and soft object with one hand only, instead of two. We predict that such patterns of response, however, will occur only in older infants when motor constraints have dissipated and motor flexibility has developed to match the perceived variations in size and texture.

We assessed infants' ability to scale their actions to object size using a psychophysical staircase procedure (Adolph, 1995). In this procedure, we presented the solid objects to the infants, one at a time, either following an incremental or decremental order in size. By doing so, we were able to determine whether infants could accommodate size increments by switching from one- to two-handed reaching (or the reverse), or, if they displayed systemic motor constraints by maintaining the same one- or two-handed reaching pattern throughout the series despite changes in object size. In the soft object condition, because the critical parameter was texture and not size, we always presented objects in a decreasing order such that we could determine whether infants would use haptic information and switch to one-handed reaching on the second trial after having manipulated the first object. Finally, because we wanted to determine whether infants made their decisions to reach based on current visual information or on previous haptic information, we tracked infants' responses during both reaching and grasping, – that is before and after contact with the target – as a function of object size for both solid and soft objects. By observing the individual, successive patterns of reaching and grasping across conditions, we were able to determine that young infants were indeed initially constrained by systemic motor tendencies that conflicted with the process of perceptual-motor mapping. Older infants, on the contrary, who were freed from these initial motor constraints, were able to use and integrate visual and haptic information into their actions to adapt object physical properties of size and texture.

2. Method

2.1. Participants

30 infants (15 males and 15 females), aged 5, 6, 7, 8, and 9 months old (±3 days) participated in the study. There were 6 infants per age group. Gender was equally balanced within each age group. All participants were healthy, full-term infants with no known motor or sensory impairment. Most of them were of Caucasian descent and from middle-class families. They were recruited by phone call via birth announcements printed in the local newspaper. All participants received a small gift for their participation.

2.2. Apparatus

Infants were tested in an infant chair that provided full trunk support while allowing free arm and leg movements. The chair was placed on the floor and was reclined 15 degrees from vertical. A mirror measuring 61 × 51 cm, vertically mounted on a tripod, was placed behind the infant, at a diagonal angle, toward one side of the infant, such that an observer placed on the other side of the infant could see the movements of the infant's opposite arm reflecting in the mirror. A Panasonic VHS camera, facing the infant from about a 45 degree angle from the infant's midline, was located on the opposite side of the mirror and provided a full view of both the infant and the mirror, so that both arms could be simultaneously recorded. One experimenter stood behind the camera, while another experimenter was seated on the floor in front of the infant.

Objects were two series of colorful, spheric toys. One series, the *solid* object series, was composed of 17 balls ranging gradually from 3.9 to 17.1 cm in diameter (the respective diameter sizes of the 17 balls from small to large were 3.9, 4.1, 4.4, 5.1, 5.6, 6.1, 6.5, 7.3, 8.1, 8.7, 10.1, 10.8, 12.4, 13.1, 14.0, 14.8, and 17.1 cm). The smaller sizes of the solid objects were easily graspable with one hand even by our youngest infants, while the larger objects needed two hands to be held. Only the middle sizes could be considered as perceptually ambiguous relative to their size.

The other series, the *soft* object series, was composed of 12 pompons made out of colorful yarn and ranging gradually from 4.4 to 16.4 cm in diameter (the respective diameter sizes of the 12 pompons from small to large were 4.4, 4.7, 5.1, 5.5, 6.0, 8.1, 9.2, 10.5, 11.3, 13.4, 14.9, 16.4 cm). The yarn forming the pompons was not dense, so that infants could easily insert their fingers in the yarn and grab the pompons with one hand. Even the large pompons could be held with one hand by our youngest infants. Therefore, both object series offered a range of small objects that were graspable with one hand, and a range of large objects that needed one or two hands to be held depending on their texture.

2.3. Design and procedure

Most infants were tested in their homes, except for two infants, whose parents preferred to come to our Infant Motor Development Laboratory. To eliminate the possibility that variations in texture would alter infants' ability to make accurate perceptual judgments about object size alone, we always began testing infants using the solid object series first, and then finished using the soft object series last.

In the solid-object condition, we assessed infants' ability to scale their response to size increments based on vision alone using a psychophysical staircase procedure similar to the one used by Adolph (1995). In this procedure, the experimenter presented a succession of objects to the infants, one at a time, at midline and shoulder height, following either an increasing or decreasing size order. At each presentation, the experimenter coded the infant reaching response as bimanual if the infant extended two arms toward the target, and as unimanual if (s)he extended only one arm toward the target. Therefore, reaching responses were always scored based on the transport portion of the reach (see Corbetta & Thelen, 1996). Because these responses were performed prior to making contact with the target, they informed us directly on infants' ability to make appropriate action decisions based on the visually perceived characteristics of the objects. Only responses that resulted in successful contact were scored. If infants refused to reach for an object, the experimenter either tried to present the object again or presented an alternative ball of closely related size until contact with the target was successfully achieved.

In this staircase procedure, object size increments of each successive trial presentation depended on the response of the previous trial. Series presentations always began with regular size increments of 4 balls beginning with the largest or smallest object. For example, in the decreasing order, the experimenter always started with the largest object first, then, presented the 4th largest, then the 8th largest, and so on, as long as the infants provided the same reaching responses. If infants continued to produce the same response, the experimenter kept using the same increments of 4 balls until the end of the series. If infants switched responses at some point in the series, say from bimanual to unimanual, the experimenter began to use smaller size increments between adjacent ball sizes around the transition point in order to determine the ball size where infants would shift from a bimanual to a unimanual response, or the reverse (see Adolph 1995, for details). For the decreasing order, the point of behavioral transition corresponded to the ball size where infants began responding unimanually, after consistently responding bimanually in prior trials. In the increasing order, the point of behavioral transition corresponded to the ball size where infants began responding bimanually, after consistently responding unimanually in prior trials. Infants were tested with the solid series using this staircase procedure both ways, that is following an increasing and decreasing order. The orders of presentation between decreasing and increasing size variations were systematically counterbalanced by subject and by age.

Because this staircase procedure depended on previous individual responses, infants received different numbers of trials, and reached for different balls at different increments. However, this procedure offered the advantage of reducing the total number of trials across conditions and thus prevented that infants would lose interest in the task before the end of testing. Overall, infants performed between 5 and 11 reaching trials in the decreasing condition (mean = 6.37, sd = 1.61), and between 5 and 14 reaching trials in the increasing condition (mean = 7.90, sd = 2.43).

In the soft-objects condition, because we wanted to specifically assess infants' ability to adapt to textural changes even if objects were large, we only presented the soft objects in a decreasing order. We always presented the largest object first, and then decreased size by increments of 3 balls until the smallest size was attained. As in the solid condition, if an infant refused to reach for a specific pompon, the experimenter used another pompon of an adjacent size, in order to obtain a response. In that condition, infants always performed between 5 and 7 reaching trials (mean = 6.0, sd = 1.02).

Finally, because in both conditions, solid and soft, we were interested in assessing whether infants would use haptic information after contact to either adjust their grip configuration, or modify their next response, we always allowed infants to touch and manipulate objects for at least 30 s after first hand contact with the object. During that 30 s period, infants had time to adjust their hand(s) around the object and eventually grasp it. Moreover, if infants grasped the objects, they were allowed to bring them to the mouth. If infants dropped the objects right away, or did not attempt to grasp them, the experimenter held the objects in front of them, in their reaching space, in order to ensure that they would have the opportunity to explore, touch and look at the objects before continuing with the next trials.

2.4. Video coding and data analyses

All *reaching responses*, that is responses performed before contact with the target that were coded as unimanual and bimanual during testing, were recoded from the videotapes by two independent coders in order to ensure data accuracy. Agreement between reaching responses coded on-line during data collection and the reaching responses coded off-line from the video was 92.5%. The recoded data, and not the ones obtained during the session, were used for further analyses. Moreover, the following behaviors were also coded from the video by the same two coders.

2.4.1.1. Grip configuration. Our definition of a grip was strictly related to the consumatory part of the behavior following contact with the target. That is, we considered a grip to have occurred only when infants were successfully able to grasp and hold the object in their own hand(s) without the help of the experimenter. If infants were adjusting their hand(s) around the object without holding it, we did not code that behavior as a grip, but considered it as part of ongoing exploring manipulatory activities. We coded the grip as unimanual if infants used one hand, and as bimanual if they used two hands to take the object from the experimenter's hands.

2.4.1.2. Transport to the mouth. When objects were grasped successfully, coders observed if infants transported the object to the mouth. Transports to the mouth were coded as bimanual if objects were brought to the mouth with two hands, and as unimanual if brought to the mouth with one hand. Transports to the mouth were coded because they provided additional information on infants' object exploration and manipulation. Transport to the mouth also informed us on whether infants modified their grip configuration as they moved the object to another location.

We checked reliability between coders on 20% of the data analyzed. The percentage of agreements between uni- and bimanual responses for reaching, grip configuration, and transport to the mouth were consistently above 90%.

3. Results

3.1. Did infants modify their reaching responses in the solid object condition as object size changed gradually over time?

Infants revealed very different levels of response sensitivity to objects' size variations in the solid object conditions. Some infants never scaled their reaching responses to object size. These infants either never switched reaching behavior, or, if they switched, their reaching patterns were not adapted to size. Another group of infants showed partial or inconsistent response scaling to object size. These were infants who did not switch behavior consistently in both increasing and decreasing orders. They switched behavior when object size changed one way, but not when it changed the other way. Finally, a third group of infants, demonstrated consistent response scaling to object size variations in both increasing and decreasing orders. These infants consistently switched behavior from two- to one-handed reaching as object size decreased and from one- to-two-handed reaching as object size increased. Table 1 presents the frequencies and percentages of the infants who demonstrated these different levels of response sensitivity to size variations as a function of age. Table 1 reveals that, at most ages, infants responded very variably to size, except at 9 months, where 83% of the infants consistently scaled their reaching responses to object size. A χ^2 comparing the frequencies of infants showing consistent response scaling to size variation with the infants showing no or inconsistent response scaling to size variation yielded to a significant age-related difference (χ^2 (4) $= 11.746$, $p = 0.019$).

These results seem compatible with previous findings showing that infants begin to adjust their reaching responses to objects' physical properties based on visual information at around 8 months old. However, to confirm such findings, we must determine whether infants' reaching responses were properly scaled to object size and whether they accurately predicted

Table 1
Frequencies (and corresponding percentages) of infants who demonstrated either consistent, inconsistent, or no response sensitivity to size variations when reaching for increasinly larger and increasingly smaller solid objects as a function of age.

	Response scaling to object size		
Age (months)	None	Inconsistent	Consistent
5	3 (50%)	2 (33%)	1 (17%)
6	4 (67%)	1 (17%)	1 (17%)
7	2 (33%)	4 (67%)	0 (0%)
8	2 (33%)	2 (33%)	2 (33%)
9	0 (0%)	1 (17%)	5 (83%)
N	11	10	9
mean age	6.27	6.9	8.00

grip configurations. To do so, we examined at which ball size infants switched reaching behavior and investigated whether reaching and grip configurations consistently matched each other at these points of transition.

3.2. Ball size and grip configuration at points of reaching transition

Fig. 1 reports the distribution of ball sizes at which infants shifted reaching patterns from unimanual to bimanual in the increasing order, or, from bimanual to unimanual in the

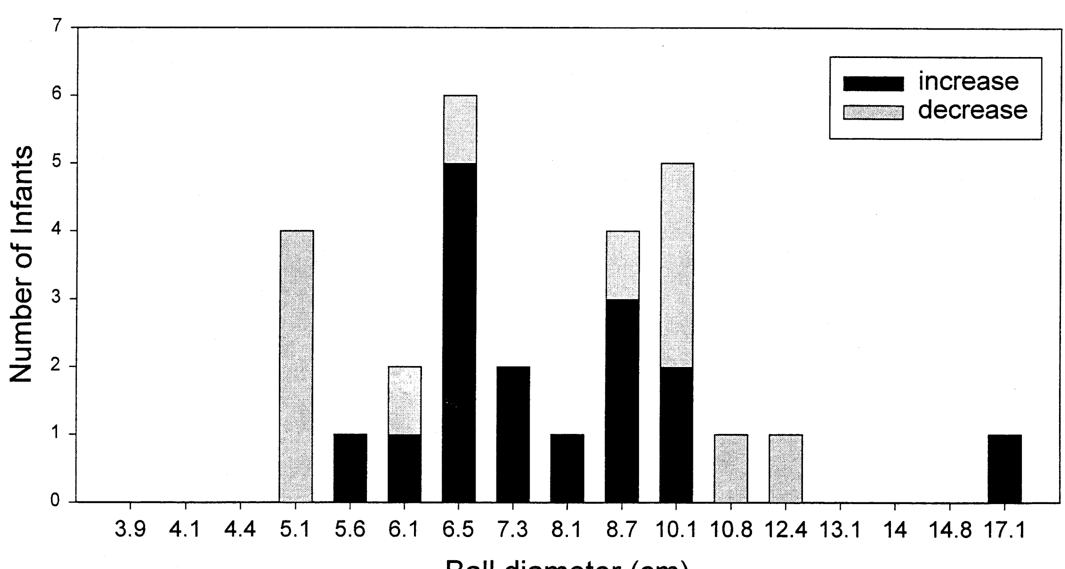

Fig. 1. Distribution of ball sizes at which infants shifted reaching patterns from one- to two- hands in the increasing order, and from two- to one-hand in the decreasing order.

Table 2
Ball diameters (average and range in cm) at which infants shifted behavior between one- and two-handed reaching are reported by size for both increasing and decreasing and decreasing presentation orders

Age (months)	Ball size (cm) at point of reaching transition Average	Range
5	8.7	6.5–12.4
6	6.83	5.1–8.1
7	6.6	5.1–8.7
8	9.08	5.1–17.1
9	5.11	5.1–10.8

decreasing order. This graph groups all the data for all infants who switched response by condition, whether infants were consistent or inconsistent at shifting reaching behavior. Fig. 1 shows that, except for one data point, infants always switched reaching behavior somewhere in the middle range sizes. There was no difference in the average ball size at which reaching transition occurred between increasing (mean = 8.14 cm (diameter), sd = 2.76) and decreasing orders (mean = 7.93 cm (diameter), sd = 2.70). There also was no difference between consistent and inconsistent groups; both groups changed reaching behavior on average at around the same ball size (Consistent group: mean = 8.1, sd = 2.28: Inconsistent group: mean = 7.99, sd = 3.43). And, there was no specific age trend either in regard to the ball size at which infants switched reaching behavior. Table 2 presents the ball sizes (diameter average and range) at which infants switched reaching behavior by age. It shows that at all ages infants shifted reaching behavior either within smaller, medium, or larger size range.

There was one difference between groups and conditions, however. It was related to the grip configurations used at the point of reaching transition. Among all the reaches performed on those particular transition trials, 86% resulted in the actual grasping of the ball. When object size increased and infants switched to two-handed reaching, they also used a two-handed configuration to grasp the objects. In contrast, when object size decreased and infants switched to one-handed reaching, only 36% of the successful grip configurations were also one-handed; the others were bimanual. This means that, in the decreasing condition, infants sometimes still needed to use their second hand to grasp the objects despite switching to one-handed reaching, while in the increasing condition they always maintained a two-handed pattern for grasping after switching to two-handed reaching. Infants who successfully switched to one-handed reaching and grasping in the decreasing condition were also infants who consistently scaled their reaching response to object size regardless of size order.

3.3. Relation between grip and reaching configurations as a function of object size

Did reach and grip configurations before and after contact with the target always shift together at the same point in the series? And what happened with the other infants who did not scale reaching responses to object size? Were they capable of adjusting their grip configuration to object size after contact with the target? Here we explore whether there was

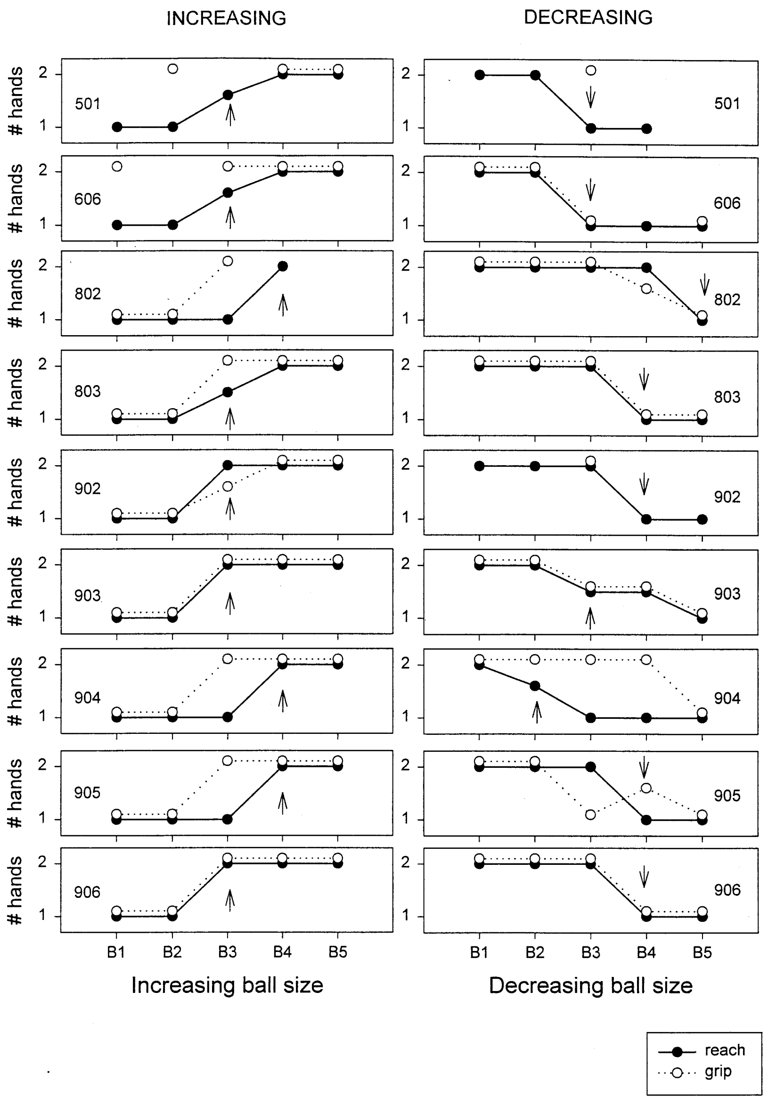

Fig. 2. One- and two-handed reaching and grasping configurations used by the 9 infants who consistently scaled their reaching response to object size. Each pair of plot displays the reaching and grasping patterns of the same infant as a function of 5 consecutive ball sizes when following an increasing order (left panel) or decreasing order (right panel). The arrows indicate the transition point at which infants switched reaching response from one to two hands for increasing ball size and from two to one hand for decreasing ball size.

some congruence between reaching and grasping patterns as a function of object size in the different groups.

Fig. 2 to 4 present the number of hands used (1 or 2) when reaching (before contact - solid line) and grasping (after contact - dotted line) for a same object as a function of increasing (left panel) or decreasing (right panel) object sizes. Because infants received different number of trials (some had as few as 5 trials) and because sometimes infants reached for different ball sizes, we labeled the ball sizes on the plots' x axes as B1, B2, B3, to B5, B6, or B7. These labels correspond to objects whose consecutive sizes are following an increasing (left panel) or decreasing (right panel) order. When data points on the y axis are between 1 and 2, it means that the same ball has been presented more than once and that infants provided different responses for each presentation, in which case, we averaged the responses. When data points are missing for the grip, that means that infants touched but did not grasp the object on those particular trials. Finally, on each plot, the 3-digit number corresponds to the subject identifier, with the first digit referring to the age of the subject.

a) *Infants who revealed consistent response scaling to object size*

Fig. 2 presents the reaching and grasping configurations used by the infants who consistently scaled their reaching response to object size. Each plot displays these responses for 5 consecutive ball sizes around the point of transition. The arrows indicate the transition point at which infants switched reaching response from one to two hands for increasing and from two to one hand for decreasing.

These 18 plots reveal that reach and grip configurations switched from one to two hands, or from two to one hand, almost around the same trial. On several plots, such as on plots 903 or 906, there is an 100% match between reaching and grasping responses, meaning that when infants changed reaching behavior, they also changed grasping behavior. This congruence between reaching and grasping responses indicates that these infants were able to make very accurate predictions about their actions in relation to the perceived object size and successfully organized their reaching and grasping responses accordingly. They shifted to two-handed reaching when they needed two hands to grasp the objects as size increased, and shifted to one hand, when they anticipated that they could use one hand for grasping these objects.

Some plots, however, such as plots 802 or 905, reveal that infants did not always shift grip and reach configurations exactly at the same trial. Sometimes, infants shifted grip configuration one ball size before shifting reaching pattern. These lags are quite revealing because they suggest that at these particular points in the series, these infants might have misjudged how many hands they needed to grasp a particular object and therefore, adjusted their grip afterward, once in contact with the target. Additionally, that infants followed up in the next trial by shifting reaching pattern in the same direction as the previous grip configuration indicates that they might have used haptic information from their previous grip configuration to plan their next reaching response. In sum, it seems that most infants in this group were either able to make appropriate decisions for action to successfully scale their response to size, or they effectively used haptic information from previous trials to modify their future reaching response to the changing object size. Only one subject, subject 904 in the decreasing condition, took more than one trial to make that adjustment. As shown on that plot, infant 904 shifted to one-handed reaching on B2 but continued to use two-handed configurations for grasping until B4. A close look at these particular data revealed that infant 904 shifted to one-handed reaching very early in the series, when the objects were still very large and still required two hands to be held. This infant's reaching and grasping strategy was to first reach and contact the object with one hand, and then bring the other arm to grasp it. Infant 904 repeated this pattern of response until the objects were small enough to be grasped with one hand. Although 904's pattern of response differed from the other infants, 904 was still able to rely on haptic information to make the correct, size-related decisions to grasp.

b) *Infants who were inconsistent at scaling their response to object size*

Fig. 3 presents the reaching and grasping configurations used by the 10 infants who demonstrated inconsistent response scaling to object size. We placed the arrows only on the plots where an appropriate transition in reaching from one to two hands for increasing or from two to one hand for decreasing was observed. Here, we also present reaching and grasping responses for a wider range of ball sizes since shifts and variations in behavioral responses either did not occur or occurred more than once.

This group presented many individual differences in response variation between conditions. It is clear that these infants did not respond systematically to size increments as did the infants in the previous group. When we examined the plots where infants did not reveal response sensitivity to size variation (when there is no arrow on the plots), we found a wide array of responses. Some infants changed reaching in the direction opposite of size increments (i.e., infants 505, 704, or 901), some switched reaching behavior more than once (i.e., infant 605 or 801), and some never switched pattern at all (i.e., infants 506 and 701). Moreover, when infants shifted behavior in a manner that was consistent with changes in object size (when there is an arrow), congruence between reaching and grasping was not systematic. Unlike the previous group, these infants' reaching and grasping responses often seemed to follow two completely different tracks. For example, some infants, such as infants 704 and 801, continued to grasp objects with two hands despite change in object size and change in reaching behavior. Other infants, in contrast, such as infants 506, 605, 701, or 801 (plots with arrows), seemed to adjust reaching and grasping patterns in relation to one another, but it took them many more trials than the previous group to generate congruent reaching and grasping responses. Does this mean that these infants relied more on haptic information to adjust their response to object size as proposed by Newell et al. (1989)? This does not seem to be the case. The fact that infants continued to use two hands for grasping objects despite size decrements, or that they needed several trials to match their reach to their grasp, seems to indicate that infants in this group made a fairly limited use of haptic information to scale their grip configuration to object size or to plan their next reach. They also were not very effective at perceptually matching their reaching response to size variations.

c) *Infants who never scaled their response to object size*

Fig. 4 presents the reaching and grasping patterns used by the 11 remaining infants who never demonstrated response sensitivity to size variations across conditions. These graphs present reaching and grasping responses for all ball sizes presented at regular increments from largest to smallest or from smallest to largest. Most infants received 6 object presentations per condition, however, one infants (603) received 7 presentations, and another infants (705) received 5 presentations for increasing.

As shown on these plots, infants in this group never or rarely modified their reaching response throughout the object series regardless of their incremental directions. They tended to adopt one form of response and applied it throughout the reaching conditions. If they adopted a one-handed reaching strategy following one order, they adopted the same reaching strategy in the other order (see infants 601 and 703). If they adopted a two-handed reaching

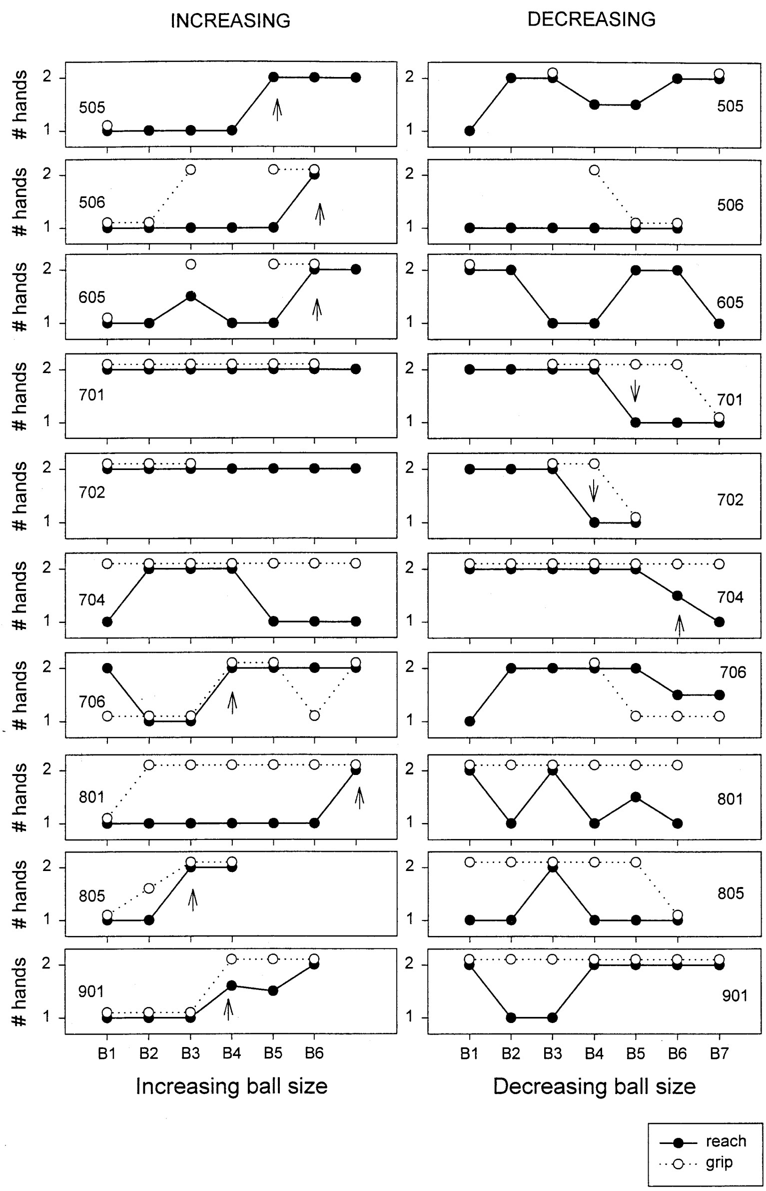

Fig. 3. One- and two-handed reaching and grasping configurations used by the 10 infants who demonstrated inconsistent response scaling to object size. Each pair of plot displays the reaching and grasping patterns of the same infant as a function of 7 consecutive ball sizes when following an increasing order (left panel) or decreasing order (right panel). The arrows on some of the plots indicate trials when transitions in reaching from one to two hands for increasing or from two to one hand for decreasing ball size were observed.

strategy when size increments were going one way, they maintained the same response strategy when size increments were going the other way (see infants 502, 602, or 705). Moreover, in many cases, these reaching tendencies seemed to apply to grasping responses

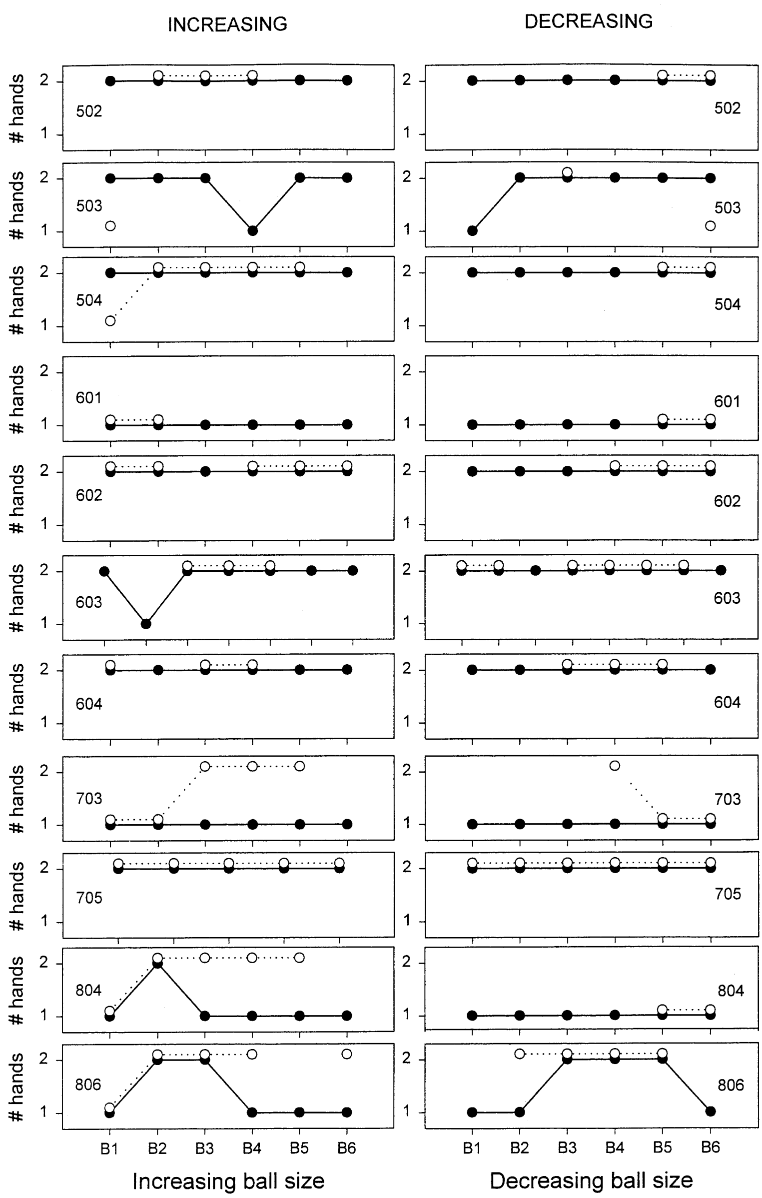

Fig. 4. One- and two-handed reaching and grasping configurations used by the 11 infants who never demonstrated response sensitivity to object size. Each pair of plot displays the reaching (solid lines) and grasping (dotted lines) patterns of the same infant as a function of 6 consecutive ball sizes when following an increasing order (left panel) or decreasing order (right panel).

as well. Therefore, it appeared that in this group, infants did not rely on either haptic or visual information to plan their reaching and grasping responses. Rather, they seemed to have responded to the tasks in a stereotypical manner regardless of object size variations. These particular results seem to confirm previous findings that young infants' motor responses are

Table 3
Frequencies (and corresponding percentages) of infants who met versus the 100% unimanual reaching criterion when reaching, for the soft objects from the second trial. Results are reported as a function of scaling performance in the solid object condition

Soft condition	Solid condition: Response scaling to object size		
100% one-handed reaching criterion	None	Inconsistent	Consistent
met	3 (27%)	0 (0%)	5 (56%)
not met	8 (73%)	10 (100%)	4 (44%)

driven by pervasive and individually defined motor constraints that supersede their perceptual abilities.

3.4. Did these patterns of response in the solid object condition predict patterns of response in the soft object condition?

The aim of the soft object condition was to test whether infants would be able to use previous haptic experience to plan future reaching patterns and subsequently adopt a one-handed response to reach for these objects in spite of their initially large size. If our interpretations in regard to the use of haptic information in the solid object condition are correct, then we should expect that only the oldest group showing consistent response scaling to object size should be able to adapt their reaching to texture. Indeed, in the solid object condition, this was the only group who seemed to effectively use haptic information from previous reaches to adapt object size on their next reach.

We anticipated that infants needed one trial to get acquainted with the textural change. Thus, if infants used two hands to reach for the first large soft object but were effectively able to use haptic information from that first object manipulation, we expected them to shift to one-handed reaching at the next object presentation, when ball size was still large (13.4 cm diameter) and to maintain this one-handed reaching mode for the remaining of the series. Since in this condition, object size was always presented following a straight decreasing order, we examined how many infants adopted and maintained a100% one-handed reaching response beginning from the second to the last object presentation.

Table 3 reports the percentage of infants who were able to meet that 100% one-handed reaching criterion from the second trial, as a function of their ability to scale their response to object size in the solid object condition. This table shows that the infants who consistently scaled their response to size variations in the solid object condition also tended to meet the 100% unimanual reaching criterion in the soft object condition more often. The other two groups of infants, who revealed either inconsistent or no response sensitivity to object size in the solid condition, did not meet this 100% unimanual reaching criterion in the soft object condition as frequently. These group differences were significant (χ^2 (2) = 7.479, p = 0.024). Patterns of response revealed that the younger infants either responded to size alone by switching to one-handed reaching later in the decreasing series, or they used mixed behaviors unrelated to size and texture, or they maintained the same one- or two-handed response consistently throughout the series despite the variations in size and texture. In other words, our results were in agreement with our predictions, that mainly infants in the older group, who demonstrated response sensitivity to size variations in the solid condition, were able to use previous haptic information to adapt their reaches in the soft condition.

3.5. Did the unimodal reaching tendencies observed in the younger infants in the solid object condition match the reaching tendencies used in the soft object condition?

In our previous analyses on the solid object condition, we found that the 11 infants who never scaled their reaching responses to object size, also displayed pervasive and individually defined tendencies to reach for these objects either always unimanually or always bimanually. Here we examined whether these tendencies were still the same in the soft condition, or if the contact and manipulation of these softer objects brought those infants to change their motor responses.

In order to compare motor tendencies within infants and across condition, we computed the total percentage of unimanual reaching responses that each infant respectively performed in each soft and solid conditions. That way, infants who responded primarily unimanually to either condition obtained a high percentage score that ranged from 83 to 100%, and infants who responded to the tasks primarily bimanually, obtained a low percentage score ranging from 0 to 17%. The other infants who used mixed one- and two-handed reaching responses like infant 806 on Fig. 4 received a middle-range score around 50%. To determine if infants responded consistently across conditions, we correlated their individual percentage scores between conditions. A Spearman Rank Order Correlation performed on these 11 data points between solid and soft conditions revealed a significant positive relation ($r = 0.781$, $p = 0.002$). In other words, infants who used predominantly two-handed behaviors to reach for solid objects such as infant 504 or 602 in Fig. 4, also used consistently two-handed behaviors to reach for the soft objects. Similarly, the infants who predominantly used one-handed behaviors to reach for the solid objects, such as infants 703 or 804, also used similar one-handed behaviors to reach for the soft objects. In sum, consistency in reaching tendencies across texture and size conditions confirmed that young infants displayed systemic motor constraints that tended to lock their reaching responses into one mode of patterning despite clearly changing and perceivable environmental properties.

3.6. Manual exploration, transport to the mouth, and object mouthing

Because we were interested in assessing whether infants were able to learn from object manipulation and improve their motor patterns accordingly – especially in the soft object condition – we always allowed them to touch, explore, or mouth the objects after they successfully contacted them or grasped them. Even infants who did not grasp the objects successfully were given the opportunity to touch them long enough before given another object. Most infants did engage in active object manipulations by batting the objects, sensing their surface using their palm and/or fingers, or attempting to grasp them. Moreover, infants who successfully grasped the objects, whether they grasped them right away or explored them first by touch, also brought the objects to their mouths on 77% of the trials. Here we ask whether infants grasped and mouthed solid and soft objects differently, which would indicate that they were sensitive to the textural differences.

Our data showed that overall, infants manipulated solid and soft objects distinctively. On average, infants grasped the softer objects more often (93% of the trials) than the solid ones (68% of the trials). These differences were significant (Mann-Whitney Rank Sum test, $T = 1890$, $p < 0.001$). Moreover, when infants were able to hold these objects in their hands, they brought the solid objects to the mouth significantly more often (58% of the time) than the soft objects (39% of the time) (Mann-Whitney Rank Sum test, $T = 1127$, $p < 0.042$). The soft objects, which were made out of yarn, were easier to grasp than the solid objects, but presumably because of their texture, infants did not bring them to their mouth as often as the solid objects. These behavioral differences suggest that infants were sensitive to the different textures and, therefore, engaged in different object manipulations depending on their feel, which is consistent with previous reports (Bushnell & Boudreau, 1993; Ruff, 1984).

Interestingly, however, the fact that infants manipulated these object differently did not seem to alter the way they continued to reach for them. We performed additional analyses on the percentage of object grasping and object mouthing by condition and by group, in order to detect whether infants who showed greater size and texture sensitivity in reaching manipulated these objects differently than the infants who did not display such reaching sensitivity. These analyses yielded to no significant differences between groups. In the *solid object condition*, for instance, infants who showed no response sensitivity to object size brought the objects to the mouth, and therefore explored these objects as often as the infants who showed response scaling to size (A Kruskal-Wallis One way ANOVA on Rank applied to the percentage of object mouthing by group revealed no significant effect of groups, $H (2) = 1.889$, $p = 0.389$). Similarly, in the *soft object condition*, infants who did not adapt to texture in reaching grasped these objects as often as the group of infants who adapted to texture (A Kruskal-Wallis One way ANOVA on Rank applied to the percentage of object grasping by group revealed no significant effect of group, $H (2) = 0.122$, $p = 0.941$). In other words, although all infants were sensitive to textural variations and *grasped* and *mouthed* these objects distinctively, these particular manipulations did not seem to modify infants' intrinsic abilities to *reach* for these objects more or less adaptively.

4. Discussion

The goal of this study was to investigate what developmental processes might account for changes in perception-action matching between 4 and 8 months old when infants are reaching and grasping for objects of different sizes and textures. Our results suggest that the developmental process by which increasingly appropriate perception-action matching emerges is tied to important changes in the motor system when reaching. Indeed, our results showed that the reaching responses of young infants were constrained by systemic one- and two-handed motor tendencies that seemed to conflict with the process of perceptual-motor mapping. We also found that when infants displayed such tendencies, they were not able to use information from previous seeing and touching to modify their response. When these motor tendencies were not present, however, infants were able to use and integrate visual and haptic information to scale their one- and two-handed actions to object size and texture.

Moreover, our analyses of infants' manipulatory activities provided additional support for the interpretation that motor constraints specific to reaching might have conflicted with the process of perceptual-motor mapping. Consistent with previous research (Bushnell & Boudreau, 1993; Ruff, 1984), our data revealed that very early, infants were sensitive to the "felt" characteristics of the objects and engaged in a number of distinctive manipulatory activities after making contact with them. In particular, we found that infants mouthed and grasped objects to different degrees depending on their texture. Our results, however, revealed that the use of distinctive manipulatory activities did not extend to reaching and grip configurations until infants were, on average, 8 months old. These particular results were not consistent with some reports showing that young infants can adjust their grip configuration to object physical properties once in contact with the target (Newell et al., 1989, 1993; Siddiqui, 1995). Also, our results do not support the interpretation that young infants rely on haptic information to adjust their grip configuration (Newell et al., 1989).

Our findings show that changes in the perceptual system alone cannot fully account for the observed behavioral changes. If one assumes that perception alone drives action matching, one also assumes (1) that infants have a full range of action patterns readily available to subserve their perceptual abilities and (2) that they are capable of appropriately selecting from these different patterns to match information from the environment. Our results clearly demonstrate that this is not the case. When reaching, young infants seem to be locked by one- or two-handed systemic motor tendencies, and seem to be limited in their ability to select and switch from one pattern to the other. It is only later, when infants are on average 8 months old and when these tendencies have completely disappeared, that they become able to display such flexibility. How can we explain the presence of these reaching tendencies? And how do they affect the developmental process of perception-action matching? We believe that an answer to these questions can be better addressed from a dynamic systems perspective, which specifically stresses the dynamic relations between perceiving and acting.

Dynamic systems theory considers behavioral changes and their underlying psychological processes as the product of continuous tensions and interactions between an organism's own constraints and the characteristics of the task at hand. Therefore, from a dynamics systems perspective, formulating a thought, planning or performing an action, does not solely result from an individual's capacity to perceive and process available information to make a decision; it will also depend on very specific characteristics intrinsic to the organism that might interact with and influence that very process of decision making (see Diedrich et al., 2000; Thelen et al., 1993, 1996, in press; Smith et al., 1999). In infants, for instance, generating a reach toward an object will directly result from the tensions and interactions between the intent of the child, his ability to perceive and detect the object's physical characteristics, and the motor capabilities that (s)he has available to respond to the task. Our data suggest that these motor capabilities are limited initially. Therefore, even if infants have the perceptual capabilities to detect significant differences in object features, when reaching, the expression of these capabilities can be limited by specific constraints arising from the motor system. As a result, infants will be able to meet the basic requirements of the task (reaching and grasping for the toy), but will not necessarily be able to fully adapt the physical characteristics of the objects. These tensions between perceiving and acting were very clear in our results, especially in the second group – the transition group – where infants were partially able to adapt perceived changes in the task demand.

What are the motor constraints that appear to lock infants into relatively inflexible patterns of one- or two-handed reaching? Several studies suggested that infants' tendencies to produce systemic one- and two-handed responses are linked to specific periods of motor learning when infants are not only trying to match their response to the environment, but they also are trying to control their body and the constraints arising from their bodily movements. Rochat (1992), for example, has shown that two-handed reaching tendencies were stronger when infants lacked self-sitting abilities. Thelen and colleagues showed that coupled tendencies in reaching also arose from infants' inability to master and control the speed of their movement (Thelen et al., 1993, 1996). Indeed, fast movements generated important biomechanical forces in the joints of their arms, thus perturbing infants' intended movement trajectory and, to some extent, their intended one- and two-handed movements (Corbetta & Thelen, 1994,1996). Finally, other studies have shown that movement perturbations and the difficulty to control movement properly were also linked to the deployment of movements and posture against gravity (Out van Soest et al., 1998; Savelsbergh & van der Kamp, 1994). All in all, these studies show that when infants are learning to reach, they are faced with tremendous movement control problems which impose obligatory constraints on their ability to adapt their actions to perceived environmental characteristics. Only when these movement control problems are solved and their associated motor constraints dissipate, can infants match their responses to perceived characteristics.

Although, in the present study, we did not measure movement kinematics or assessed infants' level of postural control, our results are consistent with the interpretation that specific motor constraints interfered with infants' ability to adapt their movements to objects' physical properties. Younger infants revealed no or limited flexibility in their reaching responses, and certainly did not seem to be able to take advantage of perceptual information (haptic and/or visual) to improve their action-environment match. Older infants on the contrary, who had acquired motor flexibility, were able to effectively use visual and haptic information to plan and adjust their movements to objects as their physical characteristics changed.

We are confident that changing motor constraints between 5 and 9 months old constitute an important factor in the observed developmental patterns, however, one could still argue that these one- and two-handed tendencies might have formed as the result of the incremental orders used in our object presentation procedure. For instance, if we began testing with the small to large objects, it might have been possible that after using several one-handed reaching patterns for smaller objects, infants might have formed an habitual reaching patterns and then adopted it for the rest of the object presentation. This was not the case. Among the 11 infants who displayed systemic one- or two-handed motor responses, 6 showed patterns that matched the size of the first object presentation, but 5 used opposite reaching patterns that did not match the size of initial object presentation. Moreover, evidence from other studies also suggest that these reaching tendencies are not task dependent. A similar inability to generate differentiated one- and two-handed responses to object size between 5 and 8 months old was reported in other studies that used randomized object size presentations

(Fagard & Pezé, 1997; Fagard & Jacquet, 1996). And, similar coordination tendencies were also observed in spontaneous movements when infants were not asked to meet specific tasks requirements (Corbetta & Thelen, 1996). Taken together, these data suggest that young infants' tendencies to systematically reach with one or two hands were not tied to specific procedural characteristics of our testing, but rather emerged from constraints that are intrinsic to the organism.

Another concern might be that we changed object size from trial to trial and infants were never presented with the same object twice in a row. Here again, one may argue that by using such procedure we limited young infants' ability to demonstrate their capacity to apply previous perceptual information to the next reach, because information gathered in relation to one object could not necessarily be applied to the next object. Again, we think that this is very unlikely. Tendencies to perform the same reaching responses were documented even in longitudinal studies that offered very predictable environments to the infants by providing repeated and identical small object presentations week after week for several consecutive months (Corbetta & Bojczyk, in press; Corbetta & Thelen, 1996; Flament, 1975; Gesell & Ames, 1947). In one study in particular (Corbetta & Thelen, 1996), despite familiarity with the task, and despite the fact that infants were allowed to touch, grasp and mouth the objects at every trial, infants continued to produce seemingly locked, two-handed responses for several weeks in a row as if they were unable to modify their reaching patterns based on previous perceptual-motor experience. Therefore, even these studies suggest that perception of these physical properties alone was not sufficient to guide infants' future actions properly. Findings from the present study are consistent with these previous reports.

Finally, a last concern relates to the result discrepancies in grip configuration between studies that found that young infants were able to adapt their grip configuration to object size (Newell et al., 1989, 1993; Siddiqui, 1995) and our study that did not find such results. Let us mention first, that our study was not the only one to find inconclusive results in regard to the adaptation of grip configuration in infants. Fagard and Jacquet (1996) also found that infants were not always able to adjust their grip configuration to object size. These conflicting results are a little harder to explain and might warrant further investigations to better understand where discrepancies might come from. But one factor that might potentially account for these discrepancies is the object sizes adopted by the different studies.

In the Newell et al.'s studies (1989, 1993) the small objects were very small (ranging between 0.5 and 1.5 cm in diameter) and the large objects were clearly large (7–9 cm). It is possible that with such objects, infants used adapted grip configurations because they did not really have a choice. The small objects could not really be grasped with two hands and the large could not be grasped with one hand, even if infants wanted to. In our study, or Fagard's study, although our large object also required two-hands to be held, our smaller objects (4 to 5 cm diameter) permitted a choice. These small objects could be grasped with one or two hands. Plus, as shown before, the use of several intermediary object sizes in a series allows for a range of mixed grasping strategies (see also Fagard & Jacquet, 1996; Newell et al., 1993). Do these variations in object's characteristics between studies have an impact on our interpretation that infants reaching tendencies interfere with infants ability to adapt their grip configuration to object size? We do not think so for two reasons. First, we think that from the moment that objects offer a choice in response, infants' tendencies will predominate because they will not prevent the child from meeting the task requirement (i.e. grabbing the toy). The question that remains open, therefore, is whether using very small objects, that do not offer a choice in response, will constrain infants to modify their own reaching tendencies. At the moment, neither Newell's study nor ours can really answer to that question.

Second, despite that issue related to object size, we think that our interpretation remains valid because if infants were truly able to rely on haptic information to adjust their grip configuration they had the opportunity to show it. In many cases they did not. Recall that in our study we always allowed infants to touch, explore, and mouth objects. Despite active haptic exploration, only older infants consistently adjusted their grip configuration to object size. Moreover, our data show that when infants brought the objects to the mouth, 70% of the grip configuration used in the transport of the object to the mouth were identical to the initial configuration used to grasp the object, suggesting that infants did not pursue further hand-object adjustments. As a matter of fact, many of the two-handed grips for small objects remained two-handed during object transport to the mouth. These results further indicate that many times infants did not use haptic information to match their grip configuration to object size. Our findings on grip configuration suggest once again that infants before 8 month, cannot fully adapt object physical characteristics because they do not have the movement flexibility to do so.

Taken together, our study shows that when looking at changes in motor patterns, it appears that developmental changes cannot be fully understood and accounted for only by pointing at changes in the use of perceptual modalities. Developmental change occurs as both action and perception interact with each other in specific and changing ways throughout development. If perception helps guide infants' actions, infants' intrinsic motor tendencies, and individual levels of motor control affect, in turn, infants' perceptual abilities.

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