Development of body knowledge as measured by arm differentiation in infants: from global to local?

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Abstract

The ability to perceive and use the body parts in an organised and differentiated manner is a precursor of body knowledge in infancy. To acquire this ability, the infant's brain might explore the perceptual consequences of its bodily actions. Undifferentiated body movements would gradually be replaced by more precise actions. Only a very few papers have tested this "global-to-local" hypothesis and none of them have so far been replicated. In this study, we assessed arm differentiation in 4-, 6- and 8-month-old infants using a new contingency detection task in which infants have to detect a contingency between one of their arms' activity and an audiovisual stimulus on a screen. We found that 4- to 8-month-old infants seem able to differentiate their arms. However, surprisingly, we were not able to show a developmental trend in arm differentiation between 4 and 8 months of age.

Key words: Body knowledge; Sensorimotor contingencies; Infants

1. Introduction

During the first years of life, infants and toddlers progressively acquire the ability to perceive and use their body to interact efficiently with their physical and social environment (Piaget, 1936/1952; Rochat & Goubet, 2000). While the importance of this ability in development cannot be disputed, its study is limited by certain difficulties. One problem is that authors have defined this ability in different ways, resulting in a multitude of overlapping concepts of body knowledge, such as body schema, body image(s), visuo-spatial body map, body semantics, etc. (see de Vignemont, 2010 for a review). Another problem is that often such notions refer to the concept of "mental representation", whereas it is not clear what is meant by this, nor how to demonstrate its existence in infants. For these reasons we prefer in the present paper to coin a new term, namely "body know-how", that we intend to be restricted to practical aspects of body knowledge that may not involve internal representations, and that may be constituted by a collection of skills. More precisely, we define "body know-how" as the ability to perceive and use the body parts in an organised and differentiated manner. In the present article we examine the hypothesis that body know-how develops from a global state where infants have fairly undifferentiated knowledge of their bodies, to a better localised form of know-how that allows infants to use their limbs in a differentiated manner. We start by reviewing studies investigating how, during the fetal stage and early infancy, infants perceive and use their bodies regardless of their ability to differentiate their body parts. We refer to these skills as *precursors* of body know-how. Then we detail the few studies that more precisely document body know-how development in the first months of life.

1.1. Body know-how in early infancy

1.1.1. Precursors of body know-how

One first precursor of body know-how is the early sensitivity of infants to the consequences of their actions. This sensitivity seems already to be present during the last three months of pregnancy and at birth, since fetuses and newborns seem implicitly aware of the consequences of some of their actions. For example, fetuses may open their mouths in anticipation when their hands approach their face (e.g. Myowa-Yamakoshi & Takeshita, 2006; see also Fagard, Esseily, Jacquey, O'Regan, & Somogyi, 2018; Reissland & Austen, 2018 for reviews) and 4-week-old infants distinguish their own spontaneous touch of their cheeks with one hand (actively self-touching) from when an experimenter touches their cheeks (external touch) (Rochat & Hespos, 1997). Around 2 months of age infants seem to become able to modulate sucking when this generates sensory changes (Rochat & Striano, 1999). Another precursor of body know-how is infants' early sensitivity to the correspondence between sensory modalities. Indeed, sensitivity to the correspondence between visual and tactile inputs of stimuli applied on their body seems already present at birth (Filippetti, Johnson, Lloyd-Fox, Dragovic & Farroni, 2013; Zmyj, Jank, Schütz-Bosbach & Daum, 2011). Filippetti et al. (2013) showed one-day-old newborns videos of upright and inverted infant faces being touched on their cheeks either in synchrony or out of synchrony with actual stroking felt on the newborn's own face. The authors showed that the newborns preferred to look at synchronous visuo-tactile stimulation rather than asynchronous stimulation, but only in the upright face condition. The visuo-tactile integration observed in Filippetti's study has also been found for other body parts (legs) in 7- and 10-month-old infants (Zmyj et al., 2011). Moreover, infants' sensitivity to the correspondence between visual and proprioceptive feedback from their body movements seems to appear around 2-3 months of life. For example, from 3 months infants are able to discriminate contingent visual feedback caused by their body movements from (temporally or spatially) non-contingent visual feedback (e.g. Bahrick & Watson, 1985; Rochat & Morgan, 1995). In sum, these studies demonstrate that fetuses and very young infants possess coarse control of their body and may be sensitive to contingent feedback from their own movements and to the correspondence between sensory modalities. However, these studies do not inform us about the degree to which infants know the precise structure of their bodies, in particular whether they can differentiate their body parts. Two types of approach have been used to answer this question: infants' responses to tactile stimuli and infants' sensitivity to sensorimotor contingencies.

1.1.2. Limb-differentiating responses to tactile stimuli

A first approach has simply been to measure infants' neural responses to tactile stimulation applied on different body parts. Thus, Saby, Meltzoff & Marshall (2015) and Meltzoff, Saby & Marshall (2018a) observed that from 2 months of age, evoked potential responses to touch stimulations on the mouth, hands and feet were organized somatotopically in a way similar to that found in adult brains. But to what extent does this neural organization have a behavioral correspondence? This has been studied via infants' motor responses to vibrotactile stimulation applied to different areas of the body. Thus, Somogyi, Jacquey, Heed, Hoffmann, Lockman, Granjon, Fagard & O'Regan (2018) showed that infants' motor responses to vibrotactile stimulation become progressively organized in a topographical manner during the first months of life. In a longitudinal study from 3 to 6 months of age these authors stimulated infants with a vibrating buzzer applied to one hand or foot. They found that at 3 months infants responded with global movements of their body and, at 5-6 months, infants responded more specifically with the hand or foot stimulated by the buzzer. Other studies showed that already at the earliest ages tested (6 months for the hands and 4 months for the feet) infants can locate an unseen vibrotactile stimulus on the hands (Bremner, Lloyd-Fox, Mareschal & Spence, 2008) and on the feet (Begum Ali, Bremner & Spence, 2015). In these studies, infants showed more manual and visual orientation toward the stimulated limb compared to the non-stimulated limb. In summary, these studies tell us that on the perceptual side, infants' body know-how seems to be established from at least 2 months of age, since infants show a topographical organisation of their body at the neural level. However, on the behavioral side, body know-how seems to become localised only around 4-6 months.

1.1.3. Limb-differentiating sensitivity to sensorimotor contingencies

Around 3-4 months infants are already able to produce task-specific actions with their limbs (for example knee flexion or extension) when these actions generate movements of a mobile above them (e.g. Thelen, 1994; Angulo-Kinzler, Ulrich & Thelen, 2002; Sargent, Schweighofer, Kubo & Fetters, 2014). But to what extent can infants specifically move one limb when only movements of this limb generate a contingent effect? Limb differentiation as regards sensitivity to sensorimotor contingencies was tested in very young infants by van der Meer, van der Weel & Lee (1995, 1996) and van der Meer (1997) who showed that in some conditions, even 2-week-old infants can specifically move one arm in order to bring it into sight. In older infants, sensitivity to sensorimotor contingencies has mainly been investigated using the "mobile" paradigm. In this paradigm, one of the infant's limbs is attached to a mobile hanging over the infant's head in such a way that moving the limb makes the mobile move in a contingent manner (Rovee & Rovee, 1969). Using this method, it has been shown that 3- to 4-month-old infants can move one limb specifically when movements of this limb activate the mobile (Rovee-Collie, Morrongiello, Aron & Kupersmidt, 1978; Angulo-Kinzler, 2001; Heathcock, Bath, Lobo & Galloway, 2005; Watanabe & Taga, 2006, 2009; Watanabe, Homae & Taga, 2011). More precisely, Watanabe & Taga (2006) found a developmental trend like that observed in Somogyi et al. (2018): when one arm was connected to the mobile, over the course of the experiment, 2-month-old infants increased the activity of their four limbs; 3-month-old infants increased the activity of their arms but not of their legs; and 4-month-old-infants increased the activity of the connected arm only. However, this ability of 3-4-month-old infants to differentiate their limbs has not been replicated in other studies using the same paradigm (in Thelen (1994) the authors found a difference between the connected and unconnected leg movements but only in velocity and not in frequency and in Angulo-Kinzler et al. (2002) the authors did not find any difference between the connected and unconnected leg movements). To our knowledge, there is no study testing limb differentiation in infants older than 4 months of age in sensorimotor contingency tasks, probably because the mobile paradigm is not adapted to older babies. Thus, it is difficult to conclude about whether 4-month-old infants differentiate their limbs and possess local body-know-how.

1.2. The present study

The aim of our study was to attempt to verify that body know-how develops in what might be called a "global-to-local" manner, i.e. from a state in which infants use their whole body in an undifferentiated way, to a differentiated state in which infants are able to use their limbs independently of each other in an adapted way. Our hypothesis is in line with the different studies cited above showing that at first infants move their whole bodies, and that later they are able to move one specific limb in response to a stimulation (Somogyi et al., 2018) or when movements of this limb produce movements of a mobile above them (Watanabe & Taga, 2006). Nevertheless, the precise age at which infants come to possess well-established local body know-how requires further investigation. In particular, there is a lack of studies assessing body know-how in infants older than 4 months of age. To better understand body know-how development after 4 months of age, we exposed 4-, 6- and 8-month-old infants to a real-time contingency between movements of one of their arms and an audiovisual stimulation displayed on a screen. An age-matched control group saw an equally salient non-contingent audiovisual stimulation. We expected first to find a difference in activity between the infants in the contingent and non-contingent groups. We expected that this difference might consist in greater activity, and/or greater increase in activity over the course of the session in the contingent group than in the non-contingent group and that the difference between groups would increase with age. However, the main purpose of the experiment was to test our main hypothesis about body know-how development, which required examining to what extent 4, 6 and 8-month-old infants were able to restrict their movements to the particular arm that controlled the contingency. We expected that with age, infants would progressively become more able to isolate the connected arm and would show greater activity and/or a greater increase in activity over the course of the session only in the connected arm.

2. Method

2.1. Participants

124 infants aged 4-8 months were recruited from a list of interested local middle- to upper-middle class families. Each family gave their written informed consent. The experimental protocol was approved by the Paris Descartes University ethics committee. Infants were assigned to the contingent or non-contingent condition as they became available until a count of at least 16 infants per age and condition was reached. This number was chosen based on numbers used in similar paradigms (10 infants in Rovee-Collier et al., 1978; 10 infants in Heathcock et al., 2005; 16 infants in Watanabe & Taga, 2006). 20 infants were excluded due to fussiness (N=13), premature birth (N=2) or technical problems (N=5) resulting in a final sample of 34 4-month-old, 35 6-month-old, and 35 8-month-old infants (see Table 1 for details).

Subjects by group and age	Contingent group		Non-contingent group	
	Included	*Excluded*	*Included*	*Excluded*
4 months	**17** 9 girls and 8 boys 121 +/- 4 days	**2** Fussiness (N=2)	**17** 9 girls and 8 boys 128 +/- 6 days	0
6 months	**18** 7 girls and 11 boys 186 +/- 7 days	**2** Fussiness (N=1) Technical (N=1)	**17** 3 girls and 14 boys 182 +/- 9 days	**6** Fussiness (N=3) Prematurity (N=1) Technical (N=2)
8 months	**17** 11 girls and 6 boys 240 +/- 11 days	**8** Fussiness (N=5) Prematurity (N=1) Technical (N=2)	**18** 7 girls and 11 boys 246 +/- 6 days	**2** Fussiness (N=2)

Table 1 - Information on participants by group (contingent or non-contingent) and age (4, 6 or 8 months of age).

2.2. Experimental set-up

The experimental booth, constructed with ceiling-to-floor black curtains, contained a table covered with black fabric and a chair in front of which were placed a 23-inch computer screen and two loudspeakers placed symmetrically on either side of the screen. Two video cameras filmed the infant from the front and above. During the experiment, infants were seated on a parent's lap in front of the screen at approximately 60 cm. On each arm, infants wore a custom-made bracelet containing an accelerometer (Mbientlab, MetaWear RG) communicating via low-energy Bluetooth 4.0 with a computer (Fig 1).

2.3. Measure of instantaneous arm activity

The accelerometers sampled the acceleration of each arm, measured in units of g (the earth's gravitational acceleration) in the x, y, and z directions, at a frequency of 50Hz, and the *instantaneous acceleration(t)* at time *t* for each arm was calculated as the square root of the sum of the squares of the x, y and z values. This value was then low-pass filtered by computing: *value(t) = 0.015 * value(t-1) + 0.985 * instantaneous acceleration(t)*. The weights 0.015 and 0.985 were chosen during a pilot study (32 infants tested) in order to reject peak values. We considered that this low-pass filtered acceleration value represented a measure of each arm's "instantaneous activity".

2.4. Contingent audiovisual stimulation

We used the "instantaneous activity" value to control an audiovisual stimulus so that it changed position on the screen in real time depending on movements of one of the infant's arms (the *connected* arm), and was independent on the movements of the other arm (the *unconnected* arm). The contingent audiovisual stimulus (Fig 1) consisted of a highly salient red-and-yellow smiley on a black background accompanied by a 2-second 20 dB bell-sound obtained from an open-access sound bank. The smiley was continually visible on the screen, and its displacement was a function of the current "instantaneous activity" level as defined above. In this way, our contingency was similar to what would happen if our smiley was a real object moved by the force exerted on it by the connected arm. More precisely, the smiley's motion was continuously subject to a "force" calculated from the activity of the connected arm and to a "friction" dependent on the displacement of the smiley itself. We used the equation: *next displacement (in pixels) = force coeff * instantaneous activity - friction coeff * previous displacement*. The coefficients of the force (0.004) and the friction (0.001) components were determined during pilot trials, and were kept the same for all infants. The direction of motion was not determined by the direction of arm motion, but changed randomly but in a way so as to keep the smiley continually on the screen. In addition to the visual contingency there was an auditory contingency. This consisted in a bell that sounded once every time the speed of the smiley on the screen passed a threshold value, and was only played again when the smiley had stopped moving and was then re-activated by the threshold being again passed. The threshold (2 pixels/20ms) was determined during pilot trials, and was kept the same for all infants.

2.5. Design and procedure

2.5.1. Design

For each of the three age groups (4, 6 and 8 months), infants were randomly assigned to the *contingent* (experimental) group or the *non-contingent* (control) group, making a total of six groups. Infants in the *contingent* group were exposed to contingent audiovisual stimulation generated by movements of their *connected* arm (Fig 1). Infants in the *non-contingent* group were exposed to a comparable but non-contingent audiovisual stimulation. This non-contingent stimulation was specific to each age group and was made by taking the stimulation created by one of the infants of the same age in the *contingent* group. Indeed, in the non-contingent condition, the amounts of movement of the smiley and of sounds increased over time and corresponded to the expected outcome in the contingent condition. This ensured the same amount of arousal in both conditions.

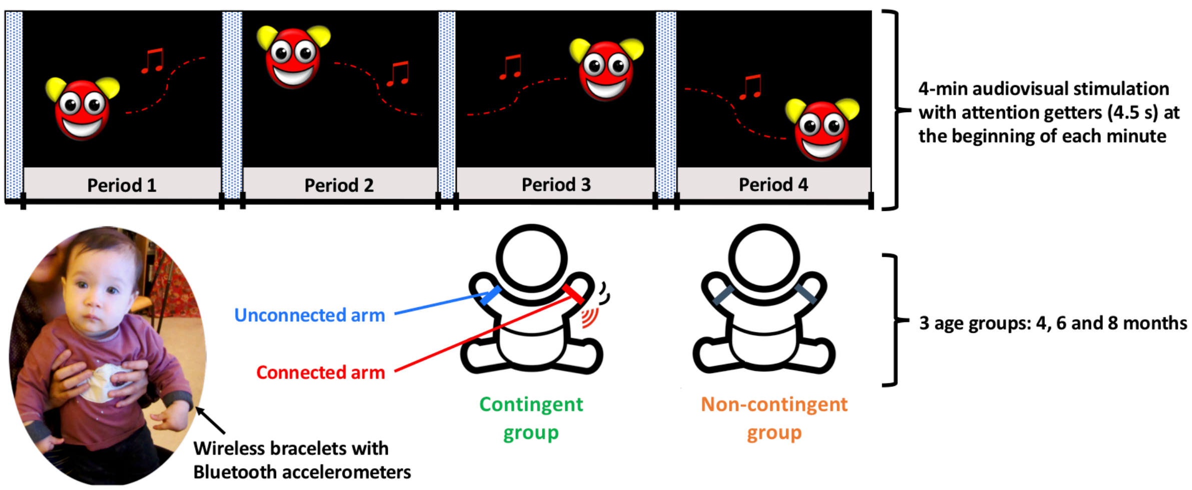

Figure 1 - We exposed 4-, 6- and 8-month-old infants to a real-time contingency between movements of one of their arms (connected arm) and an audiovisual stimulation displayed on a screen. Arm movements were measured at 50 Hz by Bluetooth-connected accelerometers worn on the baby's wrists. The experiment lasted 4 minutes separated into four periods of 55.5 seconds each. Before the beginning of each period an attention-getter of duration 4.5 seconds occurred, consisting of an expanding white disc displayed on the screen, accompanied by a metallic sound. Age-matched control groups were provided with an equally salient non-contingent audiovisual stimulation. We compared: (i) arm activity in the contingent group versus the non-contingent group and (ii) for the contingent group alone, arm activity of the connected arm versus the unconnected arm.

2.5.2. Procedure

Infants were seated on their parents' lap in front of the screen and exposed to the contingent or non-contingent audiovisual stimulation for four minutes separated into four periods of 55.5 seconds each. In order to maintain the infant's attention, an attention-getter consisting of a bright expanding white disc accompanied by a jangling keys sound was displayed at the center of the screen for 4.5 seconds before the beginning of each period. Parents were instructed to hold their infant at the waist so that both her or his arms were free, and to maintain the infant seated as much as possible. Parents were also instructed not to interact with their infant and to look down away from the screen during the experiment.

2.5.3. Data processing

Coding of looking time

The videos were analysed frame by frame using *Psycode* (http://psy.ck.sissa.it/) to ensure that infants were attentive to the experiment in each group. A second observer coded 30% of the infants' videos offline. The percentage agreement on infants' looking times between the two observers averaged 95%.

Arm activity

We averaged the instantaneous activity of each arm (see definition above) and the mean instantaneous activity of both arms (we will call this the combined arm activity) over each of the four periods of the experiment (55.5 seconds). For the contingency sensitivity assessment, we based our analysis on combined arm activity because in the non-contingent group there is no connected or unconnected arm.

3. Results

3.1. Looking time analysis

The looking time analysis confirmed that there was no difference in looking time across contingent and non-contingent groups ($F(1,103) = .076$, n.s.) and no difference across age groups ($F(2,102) = 2.119$, n.s.) or interaction ($F(2, 102)= 1.466$, n.s.).

3.2. Main results

3.2.1. Contingency sensitivity assessment

Figure 2 presents results of infants' combined arm activity over the four periods of the experiment for each group (contingent group in green and non-contingent group in orange) for all infants (Fig 2.a) and at each age (Fig 2.b). We expected that infants in the contingent group would show higher combined arm activity (calculated as the mean of both arms' activity) and/or higher increase in combined arm activity over the experiment compared to infants in the non-contingent group.

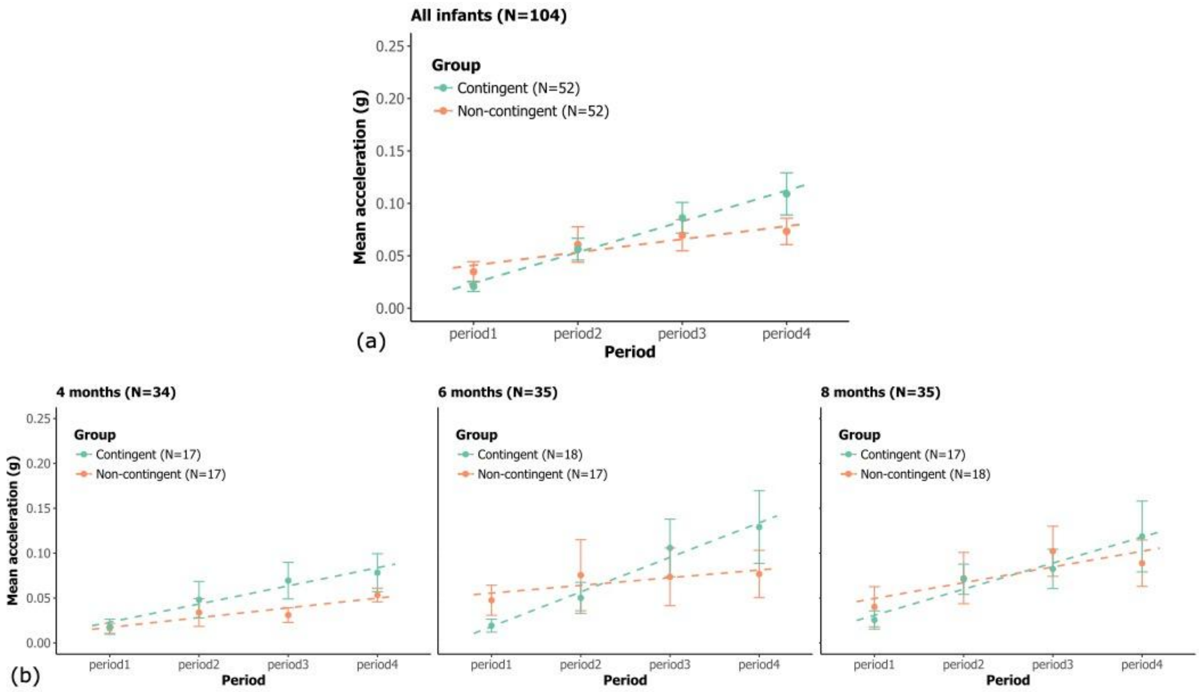

Figure 2 - Means and standard errors of the mean of the combined arm activity (calculated as the mean of both arms' activity) over the four periods of the experiment and the corresponding regression lines (dashed) for the contingent group (green) and the non-contingent group (orange). (a) all infants (b) separated by age (4, 6 and 8 months).

We see in the top graph with all infants (Fig 2.a) that combined arm activity increases over the course of the experiment in both groups and that the rate of increase of combined arm activity over the course of the experiment is higher in the contingent group as compared to the non-contingent group. Indeed, this is confirmed in a repeated measures ANOVA by a significant main effect of period ($F(2.139, 209.625) = 19.029$, $p < .001$, $\eta^2p = .163$) and a significant interaction between period and group ($F(2.139, 209.625) = 3.107$, $p = .043$, $\eta^2p = .031$). There is no significant main effect of group ($F(1, 98) = .288$, n.s.). In order to better understand the significant interaction between period and group, we did linear regressions for the combined arm activity of each infant over the four periods of the experiment. Using a one-tailed t-test, we found a significant difference in slopes of combined arm activity between the contingent and the non-contingent groups ($t(102) = 1.123$, $p = .013$). The mean of the slopes of combined arm activity in the contingent group was 0.3 (s.e.m = .046), meaning that the combined arm activity's mean in this group increased by 30% at each period of the experiment, going from 0.021 to 0.109 between the first and the last period. In the non-contingent group, the mean of the slopes of combined arm activity was 0.1 (s.e.m = .031), which means that the mean combined arm activity in this group increased by 10% at each period of the experiment, going from 0.035 to 0.073 between the first and the last period. The lower graphs (Fig 2.b) show the results separately for the three age groups. The slopes are slightly different between age groups, but this difference is not significant, as the ANOVA shows no effect of age ($F(2, 98) = 1.533$, n.s.), no interaction between group and age ($F(2, 98) = .144$, n.s.) and no interaction between period, group and age ($F(4.278, 209.625) = .991$, n.s.).

3.2.2. Assessment of arm differentiation

In this section, we present only results for the contingent group. We expected that infants who narrowed down the contingency to their connected arm should show higher arm activity or a higher increase over the experiment in arm activity for the connected arm than for the unconnected arm. Figure 3 presents infants' mean arm activity over the four periods of the experiment for each arm (connected arm in red and unconnected arm in blue) for all infants (Fig 3.a) and at each age (Fig 3.b).

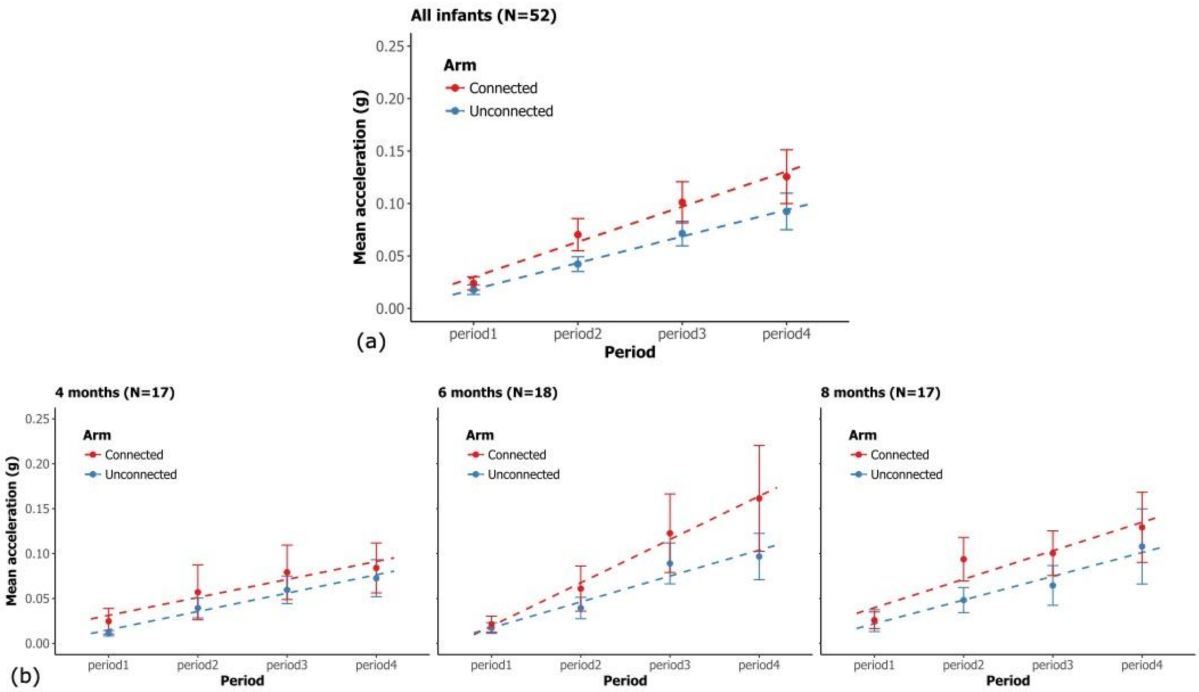

Figure 3 - Means and standard errors of the mean of each arm's activity over the four periods of the experiment and the corresponding regression lines (dashed) for the connected arm (red) and the unconnected arm (blue). (a) all infants (b) separated by age (4, 6 and 8 months).

We see in the top graph with all infants (Fig 3.a) that both arm activities increase over the course of the experiment and that the connected arm's activity is globally greater than the unconnected arm's activity. Indeed, the ANOVA shows a significant main effect of period ($F(1.655, 81.08) = 15.38$, $p < .001$, $\eta^2 p = .358$) and a significant main effect of arm ($F(1, 49) = 5.154$, $p = .028$, $\eta^2 p = .095$). We did not find an interaction between period and arm ($F(2.07, 101.428) = 2.146$, n.s.), suggesting that each arm activity increased equally over time. In the lower graphs (Fig 3.b), we see the same pattern for all age groups. The ANOVA shows no effect of age ($F(2, 49) = .435$, n.s.), no interaction between arm and age ($F(2, 49) = .185$, n.s.), and no interaction between period, arm and age ($F(4.140, 101.428) = 1.471$, n.s.). This lack of effect was also confirmed in a supplementary analysis on the rates of increase of the means of the infants' each arm activity over the four periods of the experiment.

4. Discussion

The aim of the present study was to investigate 4-, 6- and 8-month-old infants' ability to differentiate their arms when exposed to an audiovisual stimulation contingent on movements of one of their arms. First, and in order to check that infants were actually sensitive to the contingency, we compared the infants' overall arm activity to the arm activity of a control group that saw an equally salient but non-contingent audiovisual stimulation. We confirmed that infants were sensitive to the contingency. This sensitivity did not manifest itself as a higher overall arm activity in the contingent group but only as a greater increase of arm activity over the course of the experiment in the contingent group compared to the non-contingent group. This can be explained by supposing that whereas both groups of infants increased their general arousal over the course of the experiment, infants in the contingent group gradually discovered the contingency and so started moving more as compared to the non-contingent group. Interestingly, contrary to what we expected, we found no evidence that older infants were more sensitive to the contingency than younger ones. Second and as concerns the main purpose of our experiment, namely assessing arm differentiation, we found evidence for arm differentiation when age groups 4, 6 and 8 were taken together: overall, infants moved the connected arm more than the other (unconnected) arm. However, again surprisingly, we had no evidence for progression of this differentiation with age. We shall now discuss these results in more detail.

4.1. Sensitivity to sensorimotor contingencies

Our finding that infants were sensitive to our contingency is consistent with previous findings (e.g. deCasper & Fifer, 1980; Rovee & Rovee, 1969; Watson, 1972). It is worth noting that our study differs from previous work by the fact that it is the first time sensitivity to contingencies has been demonstrated using wireless accelerometers. Wireless accelerometers are a promising new tool that can be used on infants over a wide range of ages. They provide a convenient measure of motor activity and can be used to establish a variety of types of contingent stimulation (e.g. adding delays between action and feedback, testing feedback in different sensory modalities, etc.).

The result showing no statistical difference in sensitivity to the contingency across age groups is surprising. An explanation might be that the kinds of contingencies that infants are sensitive to change as a function of age (Bahrick & Watson, 1985). Indeed, at 8 months, infants are particularly interested in reaching and grasping, and spend considerable time exploring their environment via the proximal contingencies involved in hand manipulation (see, for instance, Ruff, 1984; Palmer, 1989). However, the contingency used in our study involved no hand manipulation and was distal. This might have prevented 8-month-olds from showing more sensitivity to the contingency as compared to 6- and 4-month-old infants. This might be interesting to test in future studies.

4.2. Assessment of arm differentiation

Our results show evidence that infants are able to move the particular arm that controlled the contingency more than the other arm. This is broadly compatible with other studies showing limb differentiation in infants as early as 3-4 months of age (Rovee-Collier et al., 1978; Angulo-Kinzler, 2001; Heathcock et al., 2005; Watanabe & Taga, 2006, 2009; Watanabe, Homae & Taga, 2011). However, the difference between the connected and the unconnected arm did not increase across time during the experiment, neither did it increase across age, contrary to other published studies (e.g. Heathcock et al., 2005; Watanabe & Taga, 2006). Presumably this difference derives from differences in methodologies.

A first difference between our protocol and other protocols of studies using the mobile paradigm concerns the type of contingent feedback used. In other studies, an infant's arm or leg is attached to the mobile with a ribbon. This provides local tactile stimulation every time the infant moves its connected arm or leg. This was not the case in our experiment, where our wireless technology provided no local tactile feedback to the infant's limb. The presence of co-located tactile feedback might play a critical role in the ability of young infants to narrow down a contingency to a specific limb. This hypothesis is supported by the fact that the other existing experiment on limb differentiation using a digital link failed to show evidence of limb differentiation at 3-4-months of age (Angulo-Kinzler et al., 2002). Thus, the distinction between co-located versus distal feedback would be interesting to test in future studies.

A second difference in our protocol compared to others is related to the shorter overall duration of exposure to the contingency (about 4 minutes in our experiment instead of 6 to 15 minutes during one or several sessions in studies using other protocols). This might have allowed infants less opportunity to narrow down the contingency to their connected arm. This hypothesis is supported by the results of Rovee-Collier et al. (1978) in which it is only at the end of the exposure to the contingency (4 days) that all infants showed limb differentiation. The hypothesis is also supported by a supplementary analysis we did that showed that the subset of infants that were highly active in our experiment were also those that showed arm differentiation (analysis not shown). Thus, we can suppose that if infants had had more time to explore our contingency, we might possibly have found evidence of limb differentiation comparable to that obtained in the literature.

A last explanation might come from the threshold for triggering the stimulation in our setup. Indeed, in our setup, even a very small acceleration of the connected arm produced an effect, whereas in the classical mobile paradigm only large flexion-extension movements of the limb produced an effect (e.g. in Watanabe & Taga, 2006). Thus, in our setup the contingent effect could have been produced by any arbitrary body movement provided that it resulted in a small movement of the connected arm. To check for this, we did a qualitative analysis of the videos in order to see if some infants in the contingent group repetitively adopted some particular, specific action other than moving the connected arm, and that might have triggered the audiovisual stimulus. The coder was not aware of the age (4, 6 or 8 months) nor of which arm (if any) was connected. All infant's repeated actions with a clear anticipatory behaviour toward the audiovisual effect were coded (e.g. the infant starts to kick only when the audiovisual feedback goes off, and looks at the screen in anticipation before the smiley moves). Five such movements were identified: making large head movements from right to left, moving both arms, kicking, vocalizing and moving the upper body. This supplementary qualitative analysis suggested that some infants indeed used an alternative action in order to produce the audiovisual feedback. These behaviours were mainly observed at 6 months (N=7) and 8 months (N=7) and less at 4 months (N=2). Thus, one methodological question can be raised: is it better to use a very low threshold for triggering feedback so that infants have a higher chance of discovering the contingency? Or is it better to use a high threshold so that it is easier to detect exactly which movement is generating the feedback (Watson, 1972, Zwicker et al., 2012)?

5. Conclusion

Our paper provides new insights into the development of body knowledge during early infancy. Based on the hypothesis that body know-how — the ability to perceive and use the body parts in an organised and differentiated manner — develops from global to local in the first month of life, our aim was to address the lack of studies on limb differentiation in infants older than 4 months. We demonstrated that 4- to 8-month-old infants seem able to differentiate their arms when movements of only one of their arms generate a contingent audiovisual feedback. However, we were not able to show a developmental trend in arm differentiation between 4 and 8 months of age. Our results suggest that both infants' sensitivity to sensorimotor contingencies and their ability to narrow down contingencies to a specific limb might evolve with age as a function of the infant's current sensorimotor interests. In future work, it will be interesting first to test younger infants so as to determine at what moment the global to local transition in body know-how occurs. Second, it will be interesting to test how the kinds of contingencies (e.g. analog vs. digital, local vs. distal or haptic vs. non-haptic contingencies) that infants are best at detecting and narrowing down depend on the infants' age and/or motor abilities. The wireless technology using Bluetooth accelerometers developed in this study appears to be a good tool to create such adaptable contingencies. To conclude, further work is needed to better understand how body know-how develops and is fine-tuned over the first year of life so as to provide the properly differentiated sense of the body essential for interacting with the physical and social world.

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