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Detection of visual–tactile contingency in the first year after birth

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ABSTRACT

It is well documented that in the first year after birth, infants are able to identify self-performed actions. This ability has been regarded as the basis of conscious self-perception. However, it is not yet known whether infants are also sensitive to aspects of the self when they cannot control the sensory feedback by means of self-performed actions. Therefore, we investigated the contribution of visual–tactile contingency to self-perception in infants. In Experiment 1, 7- and 10-month-olds were presented with two video displays of lifelike baby doll legs. The infant's left leg was stroked contingently with only one of the video displays. The results showed that 7- and 10-month-olds looked significantly longer at the contingent display than at the non-contingent display. Experiment 2 was conducted to investigate the role of morphological characteristics in contingency detection. Ten-month-olds were presented with video displays of two neutral objects (i.e., oblong wooden blocks of approximately the same size as the doll legs) being stroked in the same way as in Experiment 1. No preference was found for either the contingent or the non-contingent display but our results confirm a significant decrease in looking time to the contingent display compared to Experiment 1. These results indicate that detection of visual–tactile contingency as one important aspect of self-perception is present very early in ontogeny. Furthermore, this ability appears to be limited to the perception of objects that strongly resemble the infant's body, suggesting an early sensitivity to the morphology of one's own body.

1. Introduction

One of the most important aspects in a child's life is the emergence of a sense of self. Sensitivity to various aspects of the self gradually emerge from birth onwards (for an overview, see Geangu, 2008; Rochat, 2003). It has been proposed that self-perception in infancy develops on an intermodal basis and primarily in self-produced actions (Rochat & Striano, 2000). That is, by systematically exploring their own bodies and the perceptual consequences of their own actions, infants develop a sense of their own bodily self as a unique entity in the environment. The self is specified by virtue of uniquely contingent intermodal perception. For example, when one hand is touching the other, the infant receives tactile information from the stimulated hand that is temporally synchronized and spatially aligned with the manual touch. In contrast, there is no such contingent sensory feedback when another object is touched. Although there is evidence that even newborns are able to integrate visual and tactile information for object recognition (e.g., Sann & Streri, 2008; Streri & Gentaz, 2004), little is yet known about infants' ability to detect body-related visual–tactile contingency, especially in the absence of body movements.

Previous research has focused on infants' visual–proprioceptive contingency detection because this ability is regarded as a potential basis for higher-order self-perception (Bahrick & Watson, 1985). To this end, it was tested whether

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infants are able to detect contingencies between self-performed and observed movements. Bahrick and Watson (1985), for example, reported that 5-month-olds looked longer at a non-contingent video image (i.e., leg movements of a peer or delayed feedback of their own leg movements recorded prior to the experiment) than at a contingent on-line video image of their own leg movements. Follow-up studies then aimed to disentangle the relative contributions of spatial and temporal factors for this type of intermodal self-perception. It was shown that temporal (Hiraki, 2006; Zmyj, Hauf, & Striano, 2009) as well as spatial factors (Morgan & Rochat, 1997; Rochat & Morgan, 1995; Schmuckler, 1996) independently contribute to visual–proprioceptive contingency detection, and that these abilities emerge in the first 6 months after birth.

Further studies addressed the role of morphological information, such as body shape and in visual–proprioceptive contingency detection. Findings by Morgan and Rochat (1997) give rise to the supposition that morphological characteristics are a necessary prerequisite to detect intermodal contingencies between self-produced movements and the corresponding visual feedback. In this study, infants were presented with on-line feedback of their legs in a normal egocentric view and a reversed egocentric view (i.e., the left–right dimension of the visual feedback was reversed). Three- to five-month-olds were able to discriminate between the two views when morphological features of their legs were fully visible on-screen. In contrast, infants were no longer able to discriminate when they wore a pair of wide trousers hiding all characteristic features of their legs. However, Morgan and Rochat's (1997) use of baggy leggings may have obscured the actual movement itself and not only the morphological characteristics. Schmuckler and Fairhall (2001) used point light displays showing different leg movements that were either temporally and spatially congruent or incongruent with respect to the infant's own movement. Although the results for 5-month-olds for looking time were inconclusive, 7-month-olds's looking times to each display differed. These findings suggest that, at this age, motion information itself, without any other familiar perceptual characteristics of infants' own legs, is sufficient for intermodal integration.

Attentional preference for incongruent views of one's own leg movements is only present under certain conditions. Rochat and Morgan (1998), for example, reported longer looking times and more active behavior when 3- to 5-month-olds were presented with a spatially incongruent view of their own legs. However, infants preferred a perfectly contingent display when the task changed to a visual–proprioceptive guidance of the body towards a spatial target, suggesting distinct attentional mechanisms in different task contexts. From this, the authors postulated two functional orientations of self-exploration in infancy, with these being an object of exploration or an agent of action, respectively. When allowed to freely move their legs and watch the movements on a monitor, infants directed their attention primarily to the novel aspect of the visual information arising during the non-match of proprioception and vision. When aiming their feet at a target object in space, however, infants whose legs were occluded attended to the familiar (i.e., contingent visual feedback) in order to effectively guide their legs towards the object (Morgan & Rochat, 1997; Rochat & Morgan, 1998; however, see Schmuckler, 1996, for a preference for the non-contingent feedback in this paradigm).

Beyond mere self-exploration, Watson and co-workers (Bahrick & Watson, 1985; Gergely & Watson, 1999; Watson, 1972, 1994) highlighted the role of 'imperfect contingencies' in specifying social responses. Generally, the authors subdivided the level of contingency between afferent and efferent information into different subcategories: perfect contingency, imperfect contingency and non-contingency. Perfect contingency refers to a perfect correlation between efferent and afferent activity, whereas imperfect contingency entails some variation in the correlation. In contrast, non-contingency entails no correlation at all between efferent and afferent activity. The authors suggested that infants prefer imperfect contingencies between afferent and efferent information because this kind of contingency is typical of a social interactive response. In contrast, perfect contingencies are typically specific to self-related experiences, and a lack of contingency does not determine the source of the afferent information at all.

To the best of our knowledge, there is only one study that has tested infants' ability to differentiate between imperfectly contingent feedback and non-contingent feedback of their own limb movements. Schmuckler and Jewell (2007) presented 5-month-olds with two displays of a mobile, one of which was activated by the infants themselves when they performed a leg-kicking movement, while the other was a videotaped sequence of the mobile activated by another infant. The visual feedback of the mobile controlled by the infant was imperfectly contingent because temporal and spatial contingencies were only realized for some parts of the object while other parts of the mobile moved in a delayed manner with no spatial congruency to the infants' motion. Looking times revealed that infants preferentially observed the imperfectly contingent feedback in the first part of the study while this effect was absent in the second part.

In previous studies in which intermodal integration of proprioception and visual feedback was investigated, infants controlled the visual feedback by means of self-performed actions. This situation does not allow us to disentangle the relative contribution of afferent sensations and efferent motor-related information in contingency detection. That is, infants could have made their judgments solely on the basis of the efference copy of the motor signal to predict the visual feedback of their own legs (for forward models, see, for example, Blakemore, Wolpert, & Frith, 2000; von Holst & Mittelstaedt, 1950). In fact, in adults it has been proposed that efferent information is crucial for a matching of seen and simultaneously executed body movements (e.g., Tsakiris, Haggard, Franck, Mainy, & Siriguru, 2005).

The aim of the present study was to investigate whether and at what age infants are able to detect a match or mismatch of visual information and bodily sensations that arise independently from movements of their own body. To this end, we adapted a paradigm for testing the so-called rubber hand illusion (RHI, Botvinick & Cohen, 1998). The RHI is an established method for studying the bodily self and self-attribution processes in adults. It illustrates that contingent stroking of a seen rubber hand and one's own occluded hand causes a sense of ownership over the rubber hand ("feels like it is my hand") and a mislocalization of one's own hand towards the rubber hand. Thus, visual–tactile contingency is an important cue for the identification of one's own body, even if it is explicitly known that the hand observed is fake and is in fact not part of one's own body. The RHI can only be induced when the visual and tactile stroking is applied in perfect synchrony (e.g., Armel & Ramachandran, 2003) and when the rubber hand and the participant's own hand are placed at spatially congruent locations (e.g., Costantini & Haggard, 2007; Tsakiris & Haggard, 2005). It is, however, debated whether visual–tactile synchronicity is the main driver of the illusion or to what extent top-down factors such as correspondence in terms of size, texture, or orientation between the fake object and the human body also play a role (e.g., Schütz-Bosbach, Tausche, & Weiss, 2009; Tsakiris & Haggard, 2005).

In the present study, we adapted a typical RHI paradigm to test whether infants are sensitive to visual–tactile contingencies in the absence of body movements (Experiment 1), and whether morphological information about the body is important for the detection of visual–tactile contingencies (Experiment 2).

2. Experiment 1

The purpose of Experiment 1 was to test infants' sensitivity to visual–tactile intermodal perception. Infants were presented with two video displays showing the legs of a lifelike baby doll being stroked by a human hand while their own corresponding leg was also stroked. The stroking was contingent with the movements in one display and non-contingent with the other. The legs of the participating infant were occluded; the only information available to discriminate between the two video displays was the match or mismatch between the seen and felt tactile stimulation. The contingencies across modalities were mixed: For the contingent stroking, the visual–tactile relation was perfectly contingent. In contrast, the visual–proprioceptive relation was partially non-contingent because when infants occasionally moved their legs – which was unavoidable – the legs remained displayed static. Accordingly, one could describe this situation as imperfectly contingent (Watson, 1972, 1994). In the non-contingent stimulation, however, neither the visual–tactile nor the visual–proprioceptive information corresponded. This procedure differs from most previous studies on intermodal perception in two aspects. First, infants could not control the visual feedback. Second, imperfectly contingent feedback is contrasted with non-contingent feedback. Based on the findings of a previous study comparing imperfectly contingent and non-contingent feedback (Schmuckler & Jewell, 2007), we predicted that infants would pay more visual attention to the imperfectly contingent display.

2.1. Method

2.1.1. Participants

Infants were recruited from a database of parents who had agreed to participate in child development studies. Thirty-two 7-month-old infants (16 girls, 16 boys; M = 7 months 8 days; SD = 4 days) and thirty-two 10-month-old infants (13 girls, 19 boys; M = 10 months 11 days; SD = 3 days) took part. Seventeen additional 7-month-olds and ten 10-month-olds also participated in Experiment 1 but were excluded from further analyses due to fussiness (n = 13), difficulties stroking the infant's leg because of the infant's seating position or agitation (n = 8), equipment failure (n = 3), or experimenter error (n = 3). This rate of attrition (30%) is higher than in some previous studies on this topic (e.g., Bahrick & Watson, 1985: 10%) but similar to other related studies (e.g., Schmuckler, 1996: 45%; Schmuckler & Jewell, 2007: 33%). We believe that the high attrition rate in our study is due to first, the setting, as infants did not sit on a parent's lap but in an infant seat that restricted them from moving freely, and second, the unusual sensation of being stroked continuously by someone who was out of sight. Another reason for our high attrition rate was that the experimenter sometimes failed to stroke infants' legs precisely, which resulted in the exclusion of these infants from the study.

2.1.2. Stimuli

The visual stimuli (see Fig. 1) consisted of two previously recorded video displays showing the legs and the lower part of the waist of a lifelike baby doll (artist doll Nicky by Monika Levenig, HSE24).

The doll was dressed in red socks and a red T-shirt. The legs were filmed from an egocentric view (the view infants would normally see if they were looking at their legs in front of them). In both videos, the left leg was stroked. The timing of stroking was systematically varied: In the contingent display, the stimulation of the doll's leg temporally matched the stimulation delivered to the infant's leg. In the non-contingent display, there was a temporal mismatch between the seen and tactile stimulation. Stroking of the baby doll and the infants' legs was delivered manually by the experimenter (adapted from Ehrsson, Spence, & Passingham (2004)). It consisted of a series of one to four brief strokes. The strokes started below the knee and ended at the lower leg. The distance between start and end position of each stroke was approximately 10 cm. The experimenter used the index and middle finger of the right hand for stroking (see Fig. 1). Each stroke lasted for 0.5 s with a pause of 1.5 s between two consecutive strokes. The time between two series of consecutive strokes with no contact between the fingers and the legs ranged between 2.2 s and 2.8 s. The range of the temporal difference between the beginning of the series of consecutive strokes in the videos was between 0.3 s and 3 s (M = 1.3 s, SD = 650 ms). The number of strokes in each series of consecutive strokes was random in both video sequences and therefore not predictable.

Importantly, no single stroke started at the same time in the two video sequences. In order to ensure contingency between the seen and felt stroking, stroking in the contingent video sequence and the stroking of the infants' legs were guided by a computer-generated series of tones. Each tone served as an imperative cue for the experimenter to apply a single stroke. During the experiment, the

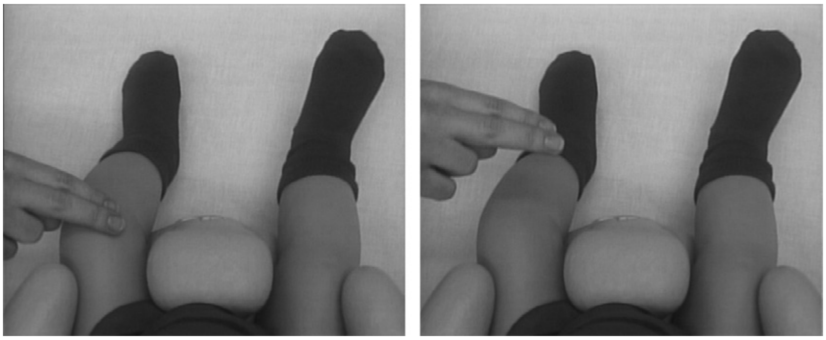

Fig. 1. Sample stimulus displays for the visual–tactile contingency task in Experiment 1 that were presented simultaneously. The respective finger positions indicate the starting position (left panel) and the end position (right panel) of the stroke.

experimenter wore earphones connected to the video display to ensure that infants could not hear the signal tones.

2.1.3. Test environment and apparatus

Each infant was tested in an experimental room surrounded by white curtains. Participants sat in an infant seat (Bumbo, BUMBO Babysitter, Toronto, Canada) that was also used during recording of the stroking of the baby doll legs. The seat was placed on a table (72 cm high) in front of two other tables of the same height. Two monitors (diameter 19 in. = 48.3 cm) were positioned on boxes (height 14.5 cm) on these tables to achieve an optimal view for the infants. The distance between the monitors and the infant's head was approximately 1 m. The monitors were positioned side by side, 18 cm apart. White cloths covered the tables and the infant seat. A video camera (board camera, VK 1312) was placed between both monitors and filmed the infant's face from 1.5 m from the floor. The two monitors were recorded by another camera that was placed behind the infants.

2.1.4. Procedure

Before the experiment started, each parent removed the infant's pants, socks and shoes and dressed them in red socks and a red T-shirt that were identical to the clothes of the doll presented in the video sequences. After the infant was placed in the infant seat, the experimenter covered the table and the infant's legs with the white cloth and positioned herself under the table out of infant's view. The cloths did not touch the infants' legs; they only obscured infants' sight of their legs. Both displays were presented for a total of 4 min. Every 30 s, both video displays were interrupted by the presentation of a flashing sun (duration 3 s) in order to maintain a constant level of attention in the infants. Relative positions of the contingent and the non-contingent video display, and the video sequence that served as contingent video were counterbalanced across infants.

2.1.5. Coding

Based on the video recordings, an observer coded how long each infant looked at the two monitors using a computerized event recorder (Interact 8.4, Mangold Software & Consulting GmbH, Arnstorf, Germany). Additionally, the observer coded the time that infants spent moving their legs, in order to measure the overall activity of the infants. A second observer, naïve to the left–right position of the contingent displays, coded one third of the videos. Inter-rater reliability for looking time and duration of leg movements was very high ($r = .99$, and $r = .97$, respectively, Intraclass correlation coefficient). For the analyses of the looking behavior, we used proportional looking time unless otherwise stated. We conducted paired sample t-tests and simple t-tests for the comparison within and between the two age groups. Overall, an alpha level of .05 was applied for statistical tests and p-values are reported two-tailed throughout the paper.

2.2. Results and discussion

Table 1 shows the mean looking time and standard deviations for the contingent and non-contingent display as well as the means and standard deviations for proportion of looking time towards the contingent view (looking at the contingent video/looking at both videos). A single sample t-test against the chance level of .50 revealed that over both age groups, the proportion of looking time towards the contingent video was above chance, $t(63) = 2.29$, $p = .03$. An independent samples t-test further revealed that the difference in the proportion of looking time towards the contingent view between 7- and 10-month-olds did not reach significance, possibly due to low statistical power, $t(62) = 0.79$, $p = .44$. In contrast, a further single sample t-test against chance level of the pro-

Table 1
Means and standard deviations for the contingent (C) and non-contingent (NC) displays for Experiments 1 and 2.

	Looking time[a]		Proportion of looking time[b]	
	C	NC	C	NC
Experiment 1				
7-month-olds	73.81 (30.03)	65.24 (24.74)	0.53 (.14)	0.47 (.14)
10-month-olds	74.98 (22.46)	61.37 (21.74)	0.55 (.13)	0.45 (.13)
Experiment 2				
10-month-olds	73.34 (24.89)	77.39 (21.97)	0.48 (.13)	0.52 (.13)

Note: Standard deviations are given in parentheses.
[a] In seconds.
[b] Looking at one video/looking at both videos.

portion of looking time revealed that the 10-month-old infants looked reliably longer at the contingent displays, $t(31) = 2.30$, $p = .03$, whereas the effect of contingency was not significant for the 7-month-olds, $t(31) = 1.01$, $p = .32$. An analysis on an individual level revealed that eighteen 7-month-olds looked longer at the contingent display and 14 looked longer at the non-contingent display, $\chi^2(1;\ N = 32) = 0.50$, $p = .48$. In contrast, twenty-one 10-month-olds looked longer at the contingent display and 11 looked longer at the non-contingent display, $\chi^2(1;\ N = 32) = 3.13$, $p = .08$.

Similar ambiguous findings between age groups have been reported by Schmuckler and Fairhall (2001). A possible explanation for this quantitative improvement at an age where infants are already able to detect the contingency between visual and motor-related information is that the integration of visual and tactile information might be more difficult. That is, in the case of most previous studies of visual–motor integration, infants actively controlled the visual feedback. Efferent motor commands allow them to control the visual feedback which, in turn, might enhance attention and the detection of a match or mismatch between the visual feedback and their own executed movement (for a similar finding in adults in a visual self-recognition task, see Tsakiris et al., 2005). In contrast, in the case of visual–tactile integration, infants cannot control the visual feedback but passively perceive afferent information.

We additionally tested whether any effects of learning occurred in the course of the stimulus presentation. In this case, one would expect higher proportional looking times towards the contingent display in the fourth minute as compared to the first minute. A paired samples t-test revealed that the proportion of looking time did not change significantly between the first ($M = 0.52$, $SD = 0.15$) and fourth minute ($M = 0.55$, $SD = 0.17$), $t(63) = 1.17$, $p = .25$. The results for both age groups separately showed the same results. Seven-month-olds' proportion of looking time to the contingent display did not change between the first and fourth minute, $t(31) = 1.21$, $p = .24$ (first minute: $M = 0.50$, $SD = 0.15$; fourth minute: $M = 0.53$, $SD = 0.16$). This was also true for the 10-month-olds, $t(31) = 0.40$, $p = .69$ (first minute: $M = 0.54$, $SD = 0.17$; fourth minute: 10-month-olds: $M = 0.56$, $SD = 0.17$).

Furthermore, we analyzed the proportional looking time for the contingent view as a function of the duration of leg movements. Since only the 10-month-olds showed a clear preference towards the contingent view, we restricted the analysis to this age group. On average, they moved their legs for 50.8 s ($SD = 34.2$). Critically, the duration of leg movements did not correlate with the proportional looking time towards the contingent display ($r = .13$, $p = .48$). This indicates that the degree of imperfectly contingent feedback caused by the leg movements did not affect the preference for the imperfectly contingent feedback. Finally, the overall looking time towards both displays did not differ between the 7-month-olds ($M = 139.06$ s, $SD = 30.53$ s) and the 10-month-olds ($M = 136.35$ s, $SD = 23.92$ s), $t(62) = 0.40$, $p = .69$. No side preference was observed in either 7-month-olds, $t(31) = 0.30$, $p = .77$, or 10-month-olds, $t(31) = 0.87$, $p = .39$.

Experiment 1 demonstrates that when collapsing data across age groups, 7- and 10-month-old infants discriminate between a contingent and a non-contingent visual–tactile display, as suggested by longer looking times for the contingent view. However, separate paired samples t-tests suggest that this ability continues to develop between 7 and 10 months of age, although this improvement is more a quantitative increase than a qualitative developmental change. Further, we found no effect of the duration of leg activity on looking preference to the contingent view. This suggests that the effect found in our study is robust against occasional leg movements. In line with this finding, it has been found that in adults, the RHI is resistant to participants' movements (e.g., Kammers, de Vignemont, Verhagen, & Dijkerman, 2009; Schütz-Bosbach, Mancini, Aglioti, & Haggard, 2006).

An important question that remains unanswered is whether the infants solely responded to the temporal and spatial match between visual and tactile feedback. An alternative possibility to this might be that similarities between morphological characteristics of the presented object and their own body may have contributed to infants' ability to detect visual–tactile contingency. We explored this in Experiment 2.

3. Experiment 2

Experiment 2 was a full replication of Experiment 1 except that we used non-body objects, that is, wooden blocks that were stroked contingently or non-contingently instead of lifelike baby doll legs. Only 10-month-old infants were tested, because they showed a more reliable visual preference for the contingent display compared to the 7-month-olds in Experiment 1. If perception of visual–tactile contingency solely depends on the matching of the temporal relation between the seen and felt stimulation, the pattern of looking preference should be identical to Experiment 1, even though, in Experiment 2, the object is unrelated to their body. In contrast, if similarity between the object presented and the infant's own body parts is significant for the integration of visual and tactile information, no looking preference for either display should occur.

3.1. Method

3.1.1. Participants

Infants were recruited from a database of parents who had agreed to participate in child development studies. Thirty-two 10-month-old infants (16 girls, 16 boys; $M = 10$ months 1 day; $SD = 9$ days) participated in Experiment 2. Fourteen additional infants participated but were excluded from further analyses due to fussiness ($n = 9$), difficulties stroking the infant because of the infant's seating position or agitation ($n = 2$), equipment failure ($n = 1$) or experimenter error ($n = 2$).

3.1.2. Stimuli, test environment and apparatus, procedure, and coding

The visual stimuli consisted of two previously recorded video displays showing two oblong wooden blocks of

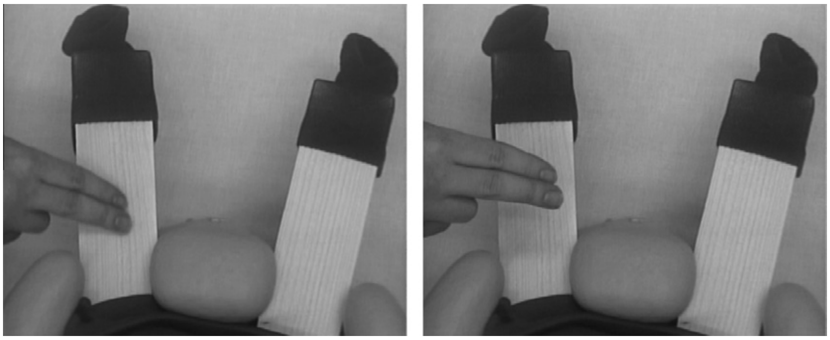

Fig. 2. Sample stimulus displays for the visual–tactile contingency task in Experiment 2 that were presented simultaneously.

approximately the same size as the baby doll legs (see Fig. 2). All other features of the videos remained the same as in Experiment 1.

We positioned the objects in the infant seat and dressed them in the red T-shirt and socks. Apparatus, procedure and coding were identical to Experiment 1. A second observer, who was naïve to the left–right position of the contingent displays, coded one third of the videos. Interrater reliability for looking time was again very high ($r = .99$, Intraclass correlation coefficient).

3.2. Results and discussion

Table 1 shows the means and standard deviations for looking time in seconds as well as for the proportion of looking time towards the contingent and non-contingent display. A single sample t-test against chance level of .50 revealed that the proportion of looking time towards the contingent video was not above chance, $t(31) = .69$, $p = .50$. Individually, 13 infants looked longer at the contingent display and 19 looked longer at the non-contingent display, $\chi^2(1;\ N = 32) = 1.13$, $p = .29$. An independent samples t-test further revealed that the proportion of looking time towards the contingent view for 10-month-olds in Experiments 1 and 2 differed significantly, $t(62) = 2.11$, $p = .04$. This finding was supported by a non-parametric comparison between the infants in Experiments 1 and 2 who preferentially looked at the contingent view, $\chi^2(1;\ N = 64) = 4.02$, $p < .05$. Additionally, the 10-month-olds looked longer at the two displays in Experiment 2, $M = 150.73$ s, $SD = 25.8$ s compared to the 10-month-olds in Experiment 1, $M = 136.35$ s, $SD = 23.9$ s, $t(62) = 2.31$, $p = .03$. In Experiment 2, there was a statistical trend for infants to generally look longer at the right display, $t(31) = 1.99$, $p = .06$.

Compared to Experiment 1, there was a significant decrease in the proportion of total looking time to the contingent display. Since the same procedure as in Experiment 1 was used with the 10-month-olds in Experiment 2 but doll legs were substituted with non-body objects, it can be concluded that 10-month-olds' detection of visual–tactile contingency depends on the morphological similarity of the perceived stimulus material to the infant's body. This result was not caused by a lack of interest in the video sequences in Experiment 2 because, in general, infants looked even longer at the video displays as compared to those in Experiment 1. Accordingly, we conclude that the infants detected the morphological difference between the life-like rubber doll legs and the blocks and no longer preferred the contingent display when the blocks were used. In contrast, in visual–proprioceptive contingency detection, the role of morphological information is probably irrelevant (Schmuckler & Fairhall, 2001; Schmuckler & Jewell, 2007; Van den Bos & Jeannerod, 2002; see Morgan & Rochat, 1997, for a different finding). However, there is an important difference between these studies and the current one. In previous studies where morphologic information was not available, infants could detect effects of their own actions. Obviously, morphologic resemblance to their own body was not necessary in detecting that the visual feedback was caused by their own action. In contrast, in the present study, participants' behavior did not correspond with the visual display. Thus, relating visual and tactile information was only rational when objects which strongly resembled the structural appearance of the own body where shown.

4. General discussion

Our findings demonstrate that in the first year after birth, infants are able to detect visual–tactile contingency in the absence of any control of the visual information. Furthermore, infants only differentiated between a contingent and non-contingent display when lifelike baby doll legs that resembled the infant's body were shown but not when wooden blocks were used as stimuli. Since adults use visual–tactile contingency detection to identify the self (Botvinick & Cohen, 1998), our results suggest that a potential basis for this ability already emerges in infancy.

In previous studies on contingency detection, infants always controlled parts of the visual feedback. It was suggested that infants predominantly detected contingency based on visual–proprioceptive perception (e.g., Bahrick & Watson, 1985). However, it was not clear whether infants merely solved these tasks based on the perceived active control over the visual feedback or if they truly matched the visual with the proprioceptive feedback. Our study demonstrates that infants are capable of detecting contingency solely based on afferent information. This ability has been described for contingency detection concerning the external space (e.g., audio-visual contingency detection, Bahrick & Lickliter, 2000), but there is a gap in the literature concerning self-related contingencies.

Although we do not know whether the infants in our study attributed the objects displayed in the video as belonging to their own body, our findings are similar to what has been reported in the context of the RHI in adults. The RHI can only be induced when participants watch a fake hand but not when the watch a neutral, non-body object (Haans, Ijsselsteijn, & De Kort, 2008; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Tsakiris & Haggard, 2005; for a single exception, see Armel & Ramachandran, 2003). In particular, it was proposed that the RHI is mediated by a match between one's own body representation and the observed object. However, it is widely agreed that in the first year after birth, infants do not have an explicit representation of the human body, in general, and their own bodily self, in particular, because their knowledge about the human body is weak (cf. Slaughter & Heron, 2004). There are claims that newborns have an innate body schema of themselves that allows matching between visual and sensori-motor representations (Meltzoff & Moore, 1997), although the experiments on which this account rests are controversial (Anisfeld, 1996; Jones, 1996). What is clear is that infants develop a sense of the normal upright view of human bodies between 5 and 9 months of age (Zieber et al., 2010). Furthermore, infants are sensitive to the structure of human body parts before the age of 9 months. Their knowledge about the structure of the body develops in relation to the relevance of the respective body part for the infant, both with regard to the self and in others (Daum & Prinz, in press). Accordingly, our findings suggest that infants are not only sensitive to the correct orientation of the human body but also to the typical structural appearance of it.

In the present study, we contrasted imperfectly contingent feedback with non-contingent feedback. The imperfect contingency condition was achieved with the presence of contingency between visual and tactile feedback and the occasional simultaneous absence of contingency between proprioceptive and visual feedback (e.g., occasions upon which infants moved their feet while the baby doll legs always remained static).[1] In contrast, in the non-contingent condition, neither visual–tactile feedback nor visual–proprioceptive feedback was contingent. Therefore, the simultaneous presentation of visual–tactile contingency and visual–proprioceptive non-contingency might have attracted infants' interest because it provoked uncertainty about whether the contingent video display was linked to the self or not. In contrast, in the non-contingent condition, no such ambiguity that might have attracted the infants' interest was present. This idea was also raised in Schmuckler and Jewell's (2007) study which also contrasted imperfect feedback that was infant-controlled and non-contingent feedback. Watson (1994) further assumed that infants appear to avoid redundant information from the perfectly contingent view and attend to non-contingent or imperfectly contingent stimuli because these possibly indicate a social response from an interaction partner. However, the visual feedback in our paradigm was independent of the infants' behavior and could not be perceived as a social response to their own behavior.

The implications of the results of the present study for our understanding of self-perception in infancy are as follows. First, in line with Rochat and Striano (2000), we assume that intermodal contingency detection entails the perception of invariant information that can be understood as a basic form of bodily self-awareness and self-identification (cf. Bermudez, Marcel, & Eilan, 1995). Whether this ability is a given (Neisser, 1991) or whether it develops via active intermodal perception and exploration (Rochat & Striano, 2000) is still a matter of debate. What is clear is that infants use their ability to detect visual–proprioceptive contingency for discrimination between their own movement and that of a peer (Bahrick & Watson, 1985; Schmuckler, 1996). We believe that visual–tactile contingency detection could be the basis for differentiating between the infant's own body and that of a peer in the absence of any movement. Second, it is known that damage to the parietal lobe disturbs self-identification of body parts in adults (Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008; Vallar & Ronchi, 2009). Importantly, this brain region processes self-specifying information by integrating visual, tactile and proprioceptive information (e.g., Iriki, Tanaka, & Iwamura, 1996; Graziano & Botvinick, 2001; Graziano, Cooke, & Taylor, 2000) and is active not only when visual–proprioceptive but also when visual–tactile contingencies are detected (Ehrsson et al., 2004; Hiraki, 2006). Third, and most importantly for the present research, is the fact that the RHI demonstrates that visual–tactile contingency perception is crucial for self-attribution processes (Haans et al., 2008). Overall, adult studies provide evidence for the supposition that the ability to detect visual–tactile contingency significantly contributes to self-perception.

In sum, the results of the present study demonstrate that based on an analysis collapsing data of both age groups, 7- and 10-month-olds are able to detect visual–tactile contingency when viewing objects strongly resembling their own body. Additionally, separate analyses of each age group show that this ability continues to improve between 7 and 10 months of age. To our knowledge, this is the first study in which infants have integrated body-related information that is exclusively based on afferent information. Moreover, these findings suggest that the sensitivity to detect a match or mismatch between visual and afferent body-related information develops at around the same age in ontogeny as the ability to detect a match or mismatch of visual and efferent motor-related information. This suggests that motor experience of actions and afferent experiences of one's own body are intricately related and both contribute to the developing perception of the self.

[1] Another source of non-contingency might have been unintended small spatial-temporal discontinuities between the experimenter's stroking and the corresponding contingent video sequence. However, in contrast to the spatial discontinuities during infants' leg movements and temporal discontinuities in the non-contingent video sequence, the spatial-temporal discontinuities provided by the experimenter were of a small magnitude.

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