INFANCY

THE OFFICIAL JOURNAL OF THE INTERNATIONAL CONGRESS OF INFANT STUDIES

Infancy, **22**(3), 389–402, 2017

ISSN: 1525-0008 print / 1532-7078 online
DOI: 10.1111/infa.12163

WILEY Blackwell

Infants' Visual Recognition of Pincer Grip Emerges Between 9 and 12 Months of Age

Irene Senna
Cognitive Neuroscience Department and Cognitive Interaction Technology-Center of Excellence
Bielefeld University and
Department of Psychology & NeuroMi
Milan Center for Neuroscience
University of Milan-Bicocca

Margaret Addabbo
Department of Psychology & NeuroMi
Milan Center for Neuroscience
University of Milan-Bicocca

Nadia Bolognini
Department of Psychology & NeuroMi
Milan Center for Neuroscience
University of Milan-Bicocca and
Laboratory of Neuropsychology
Istituto Auxologico Italiano

Elena Longhi
Department of Psychology & NeuroMi
Milan Center for Neuroscience
University of Milan-Bicocca and
Research Department of Clinical, Educational and Health Psychology
University College London

Viola Macchi Cassia and Chiara Turati
Department of Psychology & NeuroMi
Milan Center for Neuroscience
University of Milan-Bicocca

Correspondence should be sent to Irene Senna, Cognitive Neuroscience Department, and Cognitive Interaction Technology-Center of Excellence, Bielefeld University, Universitätsstrasse 25, Bielefeld D-33615, Germany. E-mail: irene.senna@uni-bielefeld.de

The development of the ability to recognize the whole human body shape has long been investigated in infants, while less is known about their ability to recognize the shape of single body parts, and in particular their biomechanical constraints. This study aimed to explore whether 9- and 12-month-old infants have knowledge of a hand-grasping movement (i.e., pincer grip), being able to recognize violations of the hand's anatomical constraints during the observation of that movement. Using a preferential looking paradigm, we showed that 12-month-olds discriminate between biomechanically possible and impossible pincer grips, preferring the former over the latter (Experiment 1). This capacity begins to emerge by 9 months of age, modulated by infants' own sensorimotor experience with pincer grip (Experiment 2). Our findings indicate that the ability to visually discriminate between pincer grasps differing in their biomechanical properties develops between 9 and 12 months of age, and that experience with self-produced hand movements might help infants in building a representation of the hand that encompasses knowledge of the physical constraints of this body part.

In our daily life, we constantly interpret social cues from body movements such as eye gaze shifts, facial expressions, manual gestures, and body postures to infer intentions and emotions of the people we interact with. Although bodies play a similar role to faces in conveying information about others' internal states (de Gelder, 2006; Slaughter, Stone, & Reed, 2004), so far the development of infants' ability to process body parts other than faces has been less explored than face processing (e.g., Johnson, Senju, & Tomalski, 2015).

A way to investigate human body perception in infancy is to study how the ability to detect violations in the human shape and its motion develops. Researchers have largely explored infants' recognition of the whole human body shape (Christie & Slaughter, 2009, 2010; Heron & Slaughter, 2010; Slaughter & Heron, 2004; Slaughter, Heron, & Sim, 2002; Slaughter, Heron-Delaney, & Christie, 2011; Zieber et al., 2010), while less attention has been devoted to infants' ability to identify violations in the shape and postures of single body parts.

The ability to recognize the whole human shape develops gradually during the first year of life (Bhatt, Hock, White, Jubran, & Galati, 2016). Infants can detect biological motion in dynamic point-light displays (PLDs) as early as few days from birth, showing a preference for biological over nonbiological motion (Simion, Regolin, & Bulf, 2008). By the age of 3 months, infants discriminate between possible and impossible whole-body configurations, presented as PLD or more realistic stimuli, such as videos, pictures, or drawings (Bertenthal, Proffitt, & Kramer, 1987; Christie & Slaughter, 2009, 2010). For instance, 3.5-month-olds discriminate between typical bodies and bodies with scrambled gross anatomy (e.g., switched location of arms and legs) or with distorted proportions (Zieber, Kangas, Hock, & Bhatt, 2015).

Focused on infants' perception of the *whole* human body shape, these studies provide support to the hypothesis that humans possess a "specialized structural description" of how the different parts of the body are arranged, specifying their relative positions and boundaries into an overall structure (Buxbaum & Coslett, 2001; Sirigu, Grafman, Bressler, & Sunderland, 1991). The ability to detect violations of the whole human body structure, as in the case of a scrambled body, requires a global, configural processing of the spatial relations among body parts, leading to the recognition of inappropriate anatomical connections between them (Reed, McGoldrick, Shackelford, & Fidopiastis, 2004; Reed, Stone, Grubb, & McGoldrick, 2006).

Unlike body structure knowledge, the ability to identify violations in the shape of single body parts *per se* has received far less attention. Being able to visually recognize violations of the biomechanical constraints of a joint or body part, such as the elbow or the hand, requires a representation of that single body part specifying its physical limits during the execution of specific movements. Identifying violations of these constraints involves local processing of body part details, rather than global processing of the entire body. In other words, such ability requires processing of featural information, defined as information regarding relatively local details, as compared to more global, spatial-relational properties of bodily stimuli.

Evidence that infants attend to featural information when observing bodily stimuli comes from studies investigating action and gesture understanding. From an early age, infants rely on the actor's hand shape to assess the goal-directedness of the observed hand actions, and to recognize communicative gestures (Ambrosini et al., 2013; Daum & Gredebäck, 2011; Daum, Vuori, Prinz, & Aschersleben, 2009; Loucks & Sommerville, 2012a,b). By 6–8 months of age, infants anticipate the goal of a reach-to-grasp action by performing proactive gaze to the action target when the hand is shaped in a whole-hand grasp or in a pincer grip, but not when the hand performs a nonfunctional closed fist reach (Ambrosini et al., 2013). Around the same age or soon after, they are able to predict the directionality of grasping actions and communicative gestures, such as pointing and give-me gestures in social interactions (e.g., Daum & Gredebäck, 2011; Daum, Ulber, & Gredebäck, 2013; Elsner, Bakker, Rohlfing, & Gredebäck, 2014).

These studies show that infants process fine details related to the surface properties of the hand to infer the intentions of the agent. However, to build a complete representation of the body and its parts, infants need to gain knowledge about how the body and its parts can and cannot move, in accordance with their biomechanical constraints. To investigate infants' knowledge of the human body parts' physical limits, some studies have assessed infants' expectations about biomechanical constraints of the arms. While 6- to 8-month-olds either fail to detect or disregard information about the biomechanical properties of the elbow during grasping actions (Southgate, Johnson, & Csibra, 2008), infants from the age of 8–12 months discriminate between arm movements that respect or violate the biomechanical constraints of the elbow (Morita et al., 2012; Reid, Belsky, & Johnson, 2005). When presented with grasping actions in which the violation of the biomechanical constraints involves the hand, 6-month-old infants are able to distinguish between possible and impossible actions (Geangu, Senna, Croci, & Turati, 2015). Even 2-day-old newborns are able to detect violations of the hand's constraints when presented with hand movements they had already experienced during prenatal life (i.e., whole-hand closure; Longhi et al., 2015).

It is likely that the early ability to discriminate between anatomically plausible and implausible hand movements is rooted in the relevance of the hand to the human species. Since birth, infants pay special attention to their own and others' hands, compared to other body parts (von Hofsten, 2004; Van der Meer, 1997), especially during hand–object interactions (Yoshida & Smith, 2008). Interestingly, infants' understanding of manual actions seems to be influenced by infants' own sensory-motor experience with the observed action (e.g., Cannon, Woodward, Gredebäck, von Hofsten, & Turek, 2011; Gerson & Woodward, 2014; Kanakogi & Itakura, 2011; Natale et al., 2014; Sommerville, Woodward, & Needham, 2005; Woodward, 1998). Sensorimotor experience might affect action perception by helping infants learning the sensory counterpart of the actions they are able to perform. Similarly, it has been suggested that the ability to perform sophisticated goal-directed actions involving specific body parts can help infants to learn the biomechanical properties of those body parts, and thus to detect violations of their physical constraints while observing similar actions (Geangu et al., 2015; Reid et al., 2005).

In light of this evidence, the present study aimed to investigate whether infants are able to recognize violations of the biomechanical properties of the fingers during the observation of a single hand movement (i.e., pincer grip) when such movement is not embedded in a goal-directed action. Indeed, while infants might be able to recognize a familiar grasp as such, the violation of the hand's anatomy might be unnoticed. To this end, in Experiment 1 we assessed whether 12-month-old infants are able to visually discriminate between an anatomically plausible pincer grip, and a similar movement violating the fingers' constraints. Such ability was assessed by means of an infant-controlled visual preference paradigm (Fantz, 1958), which consists in presenting two stimuli (here the possible and impossible hand configurations) bilaterally on the screen, and recording the length of time the infant looks at each stimulus. Stimulus discrimination is inferred by longer looking time to one stimulus than the other. Therefore, if infants are able to discriminate between the possible and the impossible pincer grip, they will spend significantly more time looking at one grip over the other.

The same procedure was used in Experiment 2 to further investigate in 9-month-old infants whether the discrimination between possible and impossible pincer grips might be influenced by infants' capability to perform this particular hand movement. Pincer grip requires the ability to move fingers individually, to grasp an object between the thumb and the index finger. Although rudimentary precursors of pincer grip appear in the first months of life (Wallace & Wishaw, 2003), it is only from the age of 9 months that the ability to execute efficient precision grips emerges (Butterworth, Verweij, & Hopkins, 1997). Therefore, Experiment 2 aims at uncovering the role of sensorimotor experience in infants' detection of the violation of fingers' constraints by exploring visual recognition of possible pincer grip in relation to infants' ability to perform pincer grips.

EXPERIMENT 1

Twelve-month-old infants' ability to visually discriminate between possible and impossible pincer grips was tested using an infant-controlled preferential looking paradigm. Infants were simultaneously presented with two videos, one showing a biomechanically possible grip, and the other displaying a biomechanically impossible version of the same movement. A preferential looking paradigm was used to establish whether infants can discriminate between the stimuli based on knowledge of the hand's biomechanical constraints that they bring to the experimental setting. Indeed, this technique rules out the possibility that infants discriminate between the stimuli based on short-term learning of the stimulus features that they develop during the experimental session, as it might happen in habituation tasks (see Christie & Slaughter, 2010). A spontaneous preference for either the possible or impossible hand configuration would allow us to conclude that infants have access to a representation of the hand that specifies how the hand should move, according to the biomechanical constraints of the fingers. A preference for the possible grip would be in line with earlier demonstrations of infants' preference for familiar motion patterns, such as human biological motion (Bertenthal, Proffitt, & Cutting, 1984; Bertenthal et al., 1987; Simion et al., 2008), biologically possible vs. impossible whole-body movements (Christie & Slaughter, 2010), and movements that are already part of infants' motor repertoire (Sanefuji, Ohgami, & Hashiya, 2008). Conversely, a preference for the impossible grip would suggest that the movement is perceived as an unfamiliar, unexpected event as compared to the overly familiar possible movement, and would be in accord with earlier demonstrations of longer looking times to unfamiliar body shapes and movements (Christie & Slaughter, 2010; Geangu et al., 2015; Longhi et al., 2015; Morita et al., 2012; Reid et al., 2005; Slaughter et al., 2002).

Materials and methods

Participants

Fourteen 12-month-old infants (nine females, mean age, M = 12 months and 7 days, standard deviation, SD = 9 days) took part in the study. Four additional infants were tested, but discarded from the final sample because they became fussy during the testing session (N = 2), watched only one of two trials (N = 1), or manifested a position bias, looking toward one direction for over 85% of their total looking time across the two trials (N = 1). Participants were all able to perform pincer grips, as stated by their parents and confirmed by a brief motor task administered at the end of the experimental session (see below). The protocol was carried out in accordance with the ethical standards of the Declaration of Helsinki (BMJ 1991; 302: 1194) and approved by the ethics committee of the University of Milan-Bicocca. Parents provided their written informed consent before the beginning of the experimental session.

Stimuli

Two videos showing a hand moving against a black background were simultaneously presented side by side on a PC monitor. The videos showed an index finger and a thumb closing either in a biomechanically possible or impossible pincer grip. To create the stimulus depicting the possible grip, seven frames were extracted from a video that recorded a female right hand performing a precision grip. The video presenting the impossible gesture was obtained by modifying the single frames with Photoshop software (Adobe Systems, San Jose, CA, USA). The first two frames were identical in both stimuli: the first frame depicted the right hand with the palm facing the observer and the fingers straight up; the second frame showed the hand rotated by 90° with respect to its vertical axis (i.e., seen from a sideway view), with the thumb facing the viewer and the other fingers aligned and oriented upward. In the following five frames, the thumb and the index finger could either close gradually until a precision grip was completed (possible grip) or bend unnaturally toward the back of the hand, violating the biomechanical properties of the phalangeal joints, until the nails of the two fingers got in contact (impossible grip) (Figure 1a). The angles of the phalanxes' displacement were matched frame by frame between the possible and impossible stimuli. Luminance, contrast, hue, and saturation were kept constant across all frames in the two videos. Each video lasted 4 sec. The mean grayscale value, calculated across the frames of each stimulus, did not differ between the possible (M = 48.4, SD = 0.66) and impossible (M = 48.1, SD = 0.31) grips (Mann–Whitney test, $U = 0$, $Z = 0$, $p = 1$). Moreover, the two videos were comparable in smoothness, as confirmed by a frame-by-frame cross-correlation calculated across successive frames in each condition (possible grip: M = 1.98, SD = 0.1; impossible grip:

M = 1.93, SD = 0.1; Mann–Whitney test, $U = 0$, $Z = 0$, $p = 1$). The size of the hand, at a distance of 60 cm, subtended a visual angle of 14.8°–15° in height and 5.3°–10.3° in width. In each frame, the palm of the hand was 12.7° from the center of the screen.

To ascertain that the stimuli were actually perceived as either biologically possible or impossible movements, 15 adults (seven female, mean age = 26.4, SD = 2.92) were asked to rate the anatomical plausibility of the stimuli on a 5-point Likert scale, where −2 and +2 indicated minimum and maximum plausibility, respectively. Results showed that the impossible grip was perceived as impossible to perform ($M = -1.93$, SD = 0.25), while the possible grip was judged as being plausible ($M = 1.93$, SD = 0.25, Wilcoxon test, $p < .001$).

Procedure

Participants sat in an infant seat at a distance of about 60 cm from a 24″ monitor (1920 × 1200 pixel resolution, refresh rate of 60 Hz) in a dimly lit room. A video camera was placed just above the monitor and recorded the infants' face. The video

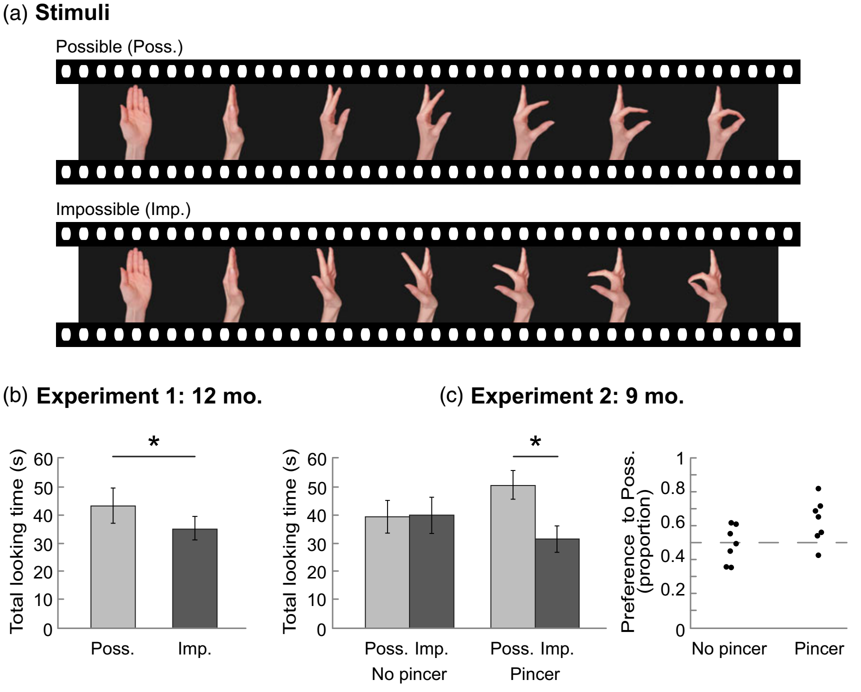

Figure 1 Stimuli and results of Experiment 1 and Experiment 2. (a) Frames composing the possible and impossible pincer grip videos. (b) Mean total looking times to the possible and impossible pincer grips shown by 12-month-old infants in Experiment 1. (c) Left panel. Mean total looking times shown by 9-month-old infants who can and cannot perform pincer grips in Experiment 2. For clarity, means are expressed in the text and in the figure as back-transformed data (i.e., seconds rather than their log transformation). Error bars represent standard errors of the mean. Right panel. Preference score for the possible stimulus shown by each individual participant in the pincer and no-pincer groups in Experiment 2. The score is calculated by dividing looking time to the possible stimulus by the sum of looking times to the possible and impossible stimuli. *$p < .05$.

camera sent live image of the participant to a second computer screen, allowing an experimenter to code infants' gaze direction online. The experimenter could see only the infants' face and was blind to the position of the stimuli on the screen. Stimulus presentation and online coding were controlled with E-prime 2 (Psychology Software Tools). An infant-controlled preferential looking paradigm was used. To catch infants' attention at the beginning of the experimental session, the experimenter presented a red circle (1.6°) flickering at a frequency of 300 ms at the center of the screen against a black background. As soon as the infant looked at it, the experimenter turned off the circle and started the video presentation. Each participant was presented with two trials. In each trial, the possible and impossible grips were shown simultaneously, one on the left and the other on the right side of the screen, then their position was switched in the following trial. The initial position of the stimuli was counterbalanced across participants. Stimuli were shown continuously, in a loop, and each trial ended when the infant watched each stimulus at least once for a minimum of 5 sec, and looked away for more than 10 sec. At the end of the first trial, the fixation point (i.e., the red circle) was presented again to catch infant's attention before presenting the second trial.

Looking time. The experimenter, who was blind to the left/right position of the stimuli on the screen, coded the duration of infant's looking times by pressing either the left or right button of the mouse according to which side of the screen the infant was looking at. When the infant stopped looking, the button was released. Video recordings of eye movements were coded offline for half of the infants by a second observer, blind to the hypotheses of the study and to the stimuli shown. Inter-rater agreement (Pearson correlation), as computed on total looking times on the two trials, was $r = 0.99$.

Grasping skills. Infants' ability to perform a pincer grip was assessed at the end of the experimental session. Infants' mothers were asked about their child's ability to perform the grip, and then, infants were engaged in a brief motor task. They sat on their mother's lap in front of a table, and one experimenter presented them with a small ring-shaped cereal. The object was placed on the table, on infants' body midline, and within a comfortable reaching distance. The experimenter attracted the infant's attention toward the object by tapping next to it or moving it. If infants did not grasp the cereal at the first attempt, the task was repeated for a maximum of five times. Grasping ability was scored with "1" or "0," depending on whether the infant was able or unable, respectively, to grasp the cereal with a pincer grip. The grip was considered as pincer if the infant grasped the object by opposing the index finger against the thumb, either with a tip-to-tip or a pad-to-pad pinch. Moreover, if the infant's grasping was ambiguous (e.g., the infant fumbled with the cereal before successively grasping it), the presentation of the object was repeated. Infants' performance was scored online by two experimenters, who were both blind to the results of the preferential looking task. There was a complete inter-rater agreement between the two experimenters. All participants were able to perform pincer grip, as reported by their mothers, and measured in the motor task.

Results and discussion

Given that the data were not normally distributed, as assessed by a Kolmogorov–Smirnov test ($p < .05$), total fixation times on the two stimuli for each of the two trial presentations were log-transformed to normalize their distribution. Data were then analyzed via an analysis of variance (ANOVA) with grip type (possible, impossible) and trial presentation (first, second) as within-subjects factors. The analysis showed a significant main effect of grip type, $F_{1,13} = 6.25$, $p = .027$, $\eta_p^2 = .22$, with longer looking times for the possible ($M = 43.41$ sec; SD = 23.25), compared to the impossible grip ($M = 35.35$ sec; SD = 15.21) (Figure 1b). The main effect of trial presentation, $F_{1,13} = 7.73$, $p = .016$, $\eta_p^2 = .7$, indicated that participants looked longer at the second ($M = 43.22$; SD = 16.66) than at the first trial ($M = 35.53$; SD = 25.36). The grip type-by-trial presentation interaction did not reach significance, $F_{1,13} = .027$, $p = .87$.

The significant preference for the possible grip was further confirmed by examination of the data for individual infants, showing that 12 of the 14 infants in the sample looked longer at the possible stimulus than at the impossible one (binomial test, $p = .006$).

The present findings indicate that 12-month-old infants are able to distinguish between biomechanically possible and impossible pincer grips. As participants were all familiar with the possible pincer grip movement, and able to perform it, one could claim that their motor ability to perform the observed hand movement may have affected their visual discrimination of the two observed grips. To test for this hypothesis, in Experiment 2 we investigated whether the attention imbalance toward the possible grip is present also at 9 months of age, when the ability to properly perform pincer grips is still developing.

EXPERIMENT 2

Experiment 2 used the same methods and stimuli used in Experiment 1 to explore whether the capability to perform pincer grip movements might affect infants' ability to visually distinguish between pincer grips either respecting or violating the biomechanical constraints of the fingers. To this end, 9-month-old infants were involved in the study, as 8–9 months is the critical time in the development of grasping abilities when pincer grasp typically emerges, mainly in the form of an "inferior pincer grip," involving a pad-to-pad, instead of a more mature tip-to-tip pinch (Butterworth et al., 1997). We tested whether the preference for the possible grip exhibited by older infants in Experiment 1 generalizes to 9-month-olds. Moreover, we hypothesized that, if sensorimotor experience with a specific movement—here the pincer grip—plays a role in the ability to visually detect the violation of physical constraints of the body part involved in such movement, 9-month-olds may show individual differences in their ability to visually discriminate between possible and impossible pincer grips as a function of their ability to perform such grasping movement. To this end, infants' ability to perform precision grip was assessed during a brief motor task at the end of the experimental session.

Materials and methods

Participants

Fourteen healthy full-term 9-month-old infants (five females, M age = 9 months and 6 days, SD = 13 days) took part in the study. Six additional infants were tested, but discarded from the final sample because they became fussy during the testing session ($N = 4$), watched only one of two trials ($N = 1$), or manifested a position bias ($N = 1$).

Stimuli and Procedure. Stimuli, procedure and behavioral measures were the same as in Experiment 1. There was a complete inter-rater agreement between the two experimenters assessing the motor performance. With respect to grasping skills, seven of the 14 (i.e., 50%) 9-month-old infants were able to perform a pincer grip. Therefore, subsequent analyses were conducted separating infants in two groups, namely able vs. unable to perform pincer grip. Infants able to perform pincer grip did not significantly differ in age from those who could not perform the grip, $t = 1.395$, $p = .19$. For 12 out of 14 infants, there was agreement between the mother's report and the infant's performance in the motor task. In the two remaining cases, the infants grasped the small cereal with a pincer grip, while their mothers have reported them being unable to perform such a grip. The two infants were scored as 1, according to the motor task's result.

Results and discussion

Because the data were not normally distributed, as assessed by a Kolmogorov–Smirnov test ($p < .05$), total fixation times were log-transformed.

Data were then analyzed via an ANOVA, with grip type (possible, impossible) and trial presentation (first, second) as within-subjects factors, and grip skill (able, unable to perform pincer grip) as between-subjects factor. The analysis revealed a significant grip type-by-grip skill interaction, $F_{1,12} = 5.02$, $p = 0.04$, $\eta_p^2 = .38$. Post hoc comparisons (Newman–Keuls) showed that infants who were able to perform the pincer grip looked longer at the possible grip ($M = 50.86$ sec; SD = 19.28) than at the impossible one ($M = 31.67$; SD = 17.71, $p = .044$). Conversely, infants who were unable to perform the pincer grip looked equally long at the possible ($M = 39.54$; SD = 21.67) and impossible grips ($M = 40.03$; SD = 24.58), $p = 0.9$ (Figure 1c). The main effect of grip type was close to significance, $F_{1,12} = 4.29$, $p = .06$, $\eta_p^2 = .32$, with an overall trend for longer looking times to the possible ($M = 45.2$ sec; SD = 20.56 sec) than to the impossible grip ($M = 35.85$ sec; SD = 20.99 sec). No other main effects or interactions were significant (all ps > .12) (Figure 1c, left panel).

Infants' preference for the possible stimulus was also analyzed by computing a preference score for each participant by dividing the looking time to the possible stimulus by the sum of the looking time to the possible and impossible stimuli. One-sample t-tests (vs. 50%) indicated that preference scores were significantly above the chance level for the group of infants who were able to perform pincer grips ($M = 63\%$; SD = 13), $t(6) = 2.61$, $p = 0.04$, but not for those unable to perform the grips ($M = 49\%$, SD = 10), $t(6) = 0.2$, $p = 0.82$. Overall, six of seven infants who were able to perform pincer grips preferred (i.e., showed a preference score larger than 50%) the possible stimulus (binomial test, $p = .055$), showing a mean preferences score of 66% (SD = 10). In contrast, only three out of the seven infants who were unable to perform pincer grips looked longer toward the possible stimulus (binomial test, $p = .27$), showing a mean preference score of 59% (SD = 3) (Figure 1c, right panel).

On average, each trial lasted 40.52 sec (SD = 17.68). Average trial duration did not differ between infants who preferred the possible grip ($M = 39.2$; SD = 11.86) and those who preferred the impossible one (M = 42.8; SD = 25.9), $t_{12} = 0.36$, $p = .72$ (two-tailed).

The present findings suggest that the ability to perform pincer grips might play a role in the visual discrimination of pincer grips either respecting or violating the fingers' biomechanical properties. In fact, the preference for the possible grip observed in Experiment 1 was evident in Experiment 2 only in the group of 9-month-old infants who were able themselves to perform the pincer grip. We cannot exclude that these infants differed from those unable to perform pincer grips for other variables, in addition to their grasping abilities; nonetheless, they did not differ in their chronological age. Furthermore, despite the small sample size, the finding that six of the seven infants in the grasping group, but only three out of the seven in the nongrasping group, showed a preference for the possible pincer grip indicates that the observed group difference is reliable.

GENERAL DISCUSSION

This study investigated whether 9- and 12-month-old infants are able to detect violations of the biomechanical properties of the fingers during the observation of pincer grips, and whether such ability might be influenced by infants' own motor experience with the observed grip. Results indicated that 12-month-old infants were able to discriminate between a biomechanically possible and an impossible pincer grip, showing a preference for the possible stimulus. Among the 9-month-old infants, those who were able to perform precision grips, as a group, looked longer at the possible grip than at the impossible one. In contrast, the group of infants who lagged behind in their grasping abilities did not show a preference for either of the two visual stimuli.

In an action context, infants discriminate between possible and impossible (i.e., violating the constraints of the fingers) grasping actions at about 6 months (Geangu et al., 2015). Of note, when exposed to possible and impossible whole-hand grasps, even 2-day-old newborns discriminate between the two (Longhi et al., 2015). Given that whole-hand grasps are part of newborns' motor repertoire, these findings suggested that sensitivity to violations of hand's physical constraints during the observation of whole-hand gestures at birth would be modulated by newborns' own sensorimotor experience with that specific grip.

The current study extends this previous evidence, showing that infants' motor skills with pincer grips affect sensitivity to violations of fingers' constraints in observed pincer grip gestures. Indeed, the ability to visually detect such violations is present at 12 months, when pincer grip is already part of infants' motor repertoire. Among 9-month-olds, infants who were able to perform pincer grips proved to be more sensitive to violations of fingers' constraints than those who were unable to perform this type of grasps. This finding is in line with previous evidence highlighting a link between sensorimotor experience and action or gesture recognition. Sensorimotor experience with the observed hand movement might facilitate infants' visual discrimination between different hand shapes. For instance, infants who are able to perform pincer grips show more anticipatory gazes to a precision grasp (Ambrosini et al., 2013), and understand its functional consequences better than those unable to perform such grips (Loucks & Sommerville, 2012a). Similarly, sensorimotor experience with self-produced actions seems to play a role in the development of the ability to detect violations of the human anatomy during goal-directed actions: infants with good grasping skills (Geangu et al., 2015), or with overall relative high motor skills (Reid et al., 2005) discriminate better than less skilled infants between possible and impossible reaching and grasping actions. Along this line, our findings suggest that infants' motor experience with pincer grips plays a role in their ability to recognize violations in the fingers' anatomical constraints, even during the execution of intransitive movements.

It might be argued that infants' ability to discriminate between hand movements differing in their biomechanical properties may reflect some unspecific maturational processes affecting both the emergence of a new motor skill (here the ability to perform pincer grip) and changes in the way in which that movement is visually processed. However, previous evidence showing that motor training influences the interpretation of actions in infants (Libertus & Needham, 2010, 2011; Sommerville, Hildebrand, & Crane, 2008; Sommerville et al., 2005) indicates that the opportunity to experience new actions or movements affects action perception, over and above unspecific maturational processes. Our results suggest that sensorimotor experience might exert a key role also in shaping infants' visual ability to discriminate between possible and impossible hand movements.

The present study highlights for the first time the influence of sensorimotor experience with pincer grips on infants' ability to visually detect violations of fingers' constraints during pincer grips. Future studies are necessary to further characterize the role of grasping skills in such visual discrimination ability, going beyond the simple dichotomous scoring system (able/unable) adopted here to measure infants' pincer grasp abilities. For instance, featuring the level of maturity of the pincer grip (i.e., differentiating between inferior pad-to-pad, or superior tip-to-tip types of pincer grasps), or considering the number of attempts made by the infant before making a successful grasp might allow a better understanding of the relationship between grasping abilities and looking preferences. In the present study, three of the seven infants who were unable to perform pincer grip showed a preference for the possible grip. With our dichotomous score, we cannot exclude that those three infants differ from the others included in the nongrasping group in some subtle motor skills that our scoring system did not capture. A more sensitive scoring system, together with a greater sample size, might provide a deeper understanding of the link between grasping skills and the ability to visually detect violations of the fingers' constraints.

Which aspects of infants' previous sensorimotor experience are likely related to their understanding of the biomechanical constraints of the hand? The fact that even newborns are able to visually discriminate between a grip they have already experienced and one violating hand's constraints (Longhi et al., 2015) might indicate that active experience with intentional actions is not necessary in order to drive such ability. Importantly, this suggests that proprioceptive and tactile counterparts of movements might have played the pivotal role. Indeed, while newborns have gained extensive tactile- and proprioceptive-motor experience *in utero*, they do not have a comparable visual experience. Later on, infants' predisposition to pay attention to and visually explore their hands from the very first days of life (von Hofsten, 2004; Van der Meer, 1997) likely contributes to the active learning of the association between the motor and visual components of self-generated movements; this ability, in turn, might guide the development of a more complex and complete body representation.

Unlike previous studies, we used an intransitive movement, consisting in a hand presented alone, detached from the whole body and in the absence of any object (thus avoiding object affordances) or communicative context. The ability to discriminate between biomechanically possible and impossible pincer grips requires not only knowledge of the hand gesture, but also knowledge of the biomechanical constraints of the body part performing the movement. In our daily life, we constantly interpret others' manual gestures, even when they are not directed to a specific target: To do so, we recognize hand configurations and attribute a meaning to them. The spontaneous preference for a possible, familiar hand movement found in our study implies the knowledge of that movement: in order to be able to recognize violations in the hand's shape during a precision grip, infants must have access to a representation of how the hand can move during the execution of such a grip. Therefore, our results indicate that the ability to recognize violations in the biomechanical constraints of the fingers during the observation of pincer grips emerges between 9 and 12 months of age. They also suggest that the ability to discriminate between possible and impossible hand gestures might be supported by the sensorimotor representation of infants' own hand movements, likely derived by infants' own motor experience. Experience with self-produced hand movements might provide infants with a unique insight into the biomechanical properties of that body part, helping them to develop knowledge about how body parts can or cannot move.

ACKNOWLEDGMENTS

The authors thank Carlo Toneatto for technical support, and Eleonora Frasson, Ioana Cristina Marchis, and Cesare Parise for assistance. We are grateful to the families who kindly participated in this study. This research was supported by a European Research Council (ERC) Starting Grant (ODMIR No. 241176) awarded to Chiara Turati.

REFERENCES

Ambrosini, E., Reddy, V., de Looper, A., Costantini, M., Lopez, B., & Sinigaglia, C. (2013). Looking ahead: Anticipatory gaze and motor ability in infancy. *PLoS One*, *8*, e67916.

Bertenthal, B.I., Proffitt, D.R., & Cutting, J.E. (1984). Infant sensitivity to figural coherence in biomechanical motions. *Journal of Experimental Child Psychology*, *37*, 213–230.

Bertenthal, B.I., Proffitt, D.R., & Kramer, S.J. (1987). Perception of biomechanical motions by infants: Implementation of various processing constraints. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 577–585.

Bhatt, R.S., Hock, A., White, A., Jubran, R., & Galati, A. (2016). The development of body structure knowledge in infancy. *Child Development Perspectives*, *10*, 45–52.

Butterworth, G., Verweij, E., & Hopkins, B. (1997). The development of prehension in infants: Halverson revisited. *British Journal of Developmental Psychology*, *15*, 223–236.

Buxbaum, L.J., & Coslett, H.B. (2001). Specialized structural description for human body parts: Evidence from autotopagnosia. *Cognitive Neuropsychology*, *18*, 289–306.

Cannon, E.N., Woodward, A.L., Gredebäck, G., von Hofsten, C., & Turek, C. (2011). Action production influences 12-month-old infants' attention to others' actions. *Developmental Science*, *15*, 35–42.

Christie, T., & Slaughter, V. (2009). Exploring links between sensorimotor and visuospatial body representations in infancy. *Developmental Neuropsychology*, *34*, 448–460.

Christie, T., & Slaughter, V. (2010). Movement contributes to infants' recognition of the human form. *Cognition*, *114*, 329–337.

Daum, M.M., & Gredebäck, G. (2011). The development of grasping comprehension in infancy: Covert shifts of attention caused by referential actions. *Experimental Brain Research*, *208*, 297–307.

Daum, M.M., Ulber, J., & Gredebäck, G. (2013). The development of pointing perception in infancy: Effects of communicative signals on covert shifts of attention. *Developmental Psychology*, *49*, 1898–1908.
Daum, M.M., Vuori, M.T., Prinz, W., & Aschersleben, G. (2009). Inferring the size of a goal object from an actor's grasping movement in 6- and 9-month-old infants. *Developmental Science*, *12*, 854–862.
de Gelder, B. (2006). Towards the neurobiology of emotional body language. *Nature Reviews Neurosciences*, *7*, 242–249.
Elsner, C., Bakker, M., Rohlfing, K., & Gredebäck, G. (2014). Infants' online perception of give-and-take interactions. *Journal of Experimental Child Psychology*, *126*, 280–294.
Fantz, R.L. (1958). Pattern vision in young infants. *The Psychological Record*, *8*, 43–47.
Geangu, E., Senna, I., Croci, E., & Turati, C. (2015). The effect of biomechanical properties of motion on infants' perception of goal-directed grasping actions. *Journal of Experimental Child Psychology*, *129*, 55–67.
Gerson, S.A., & Woodward, A.L. (2014). Learning from their own actions: The unique effect of producing actions on infants' action understanding. *Child Development*, *85*, 264–277.
Heron, M., & Slaughter, V. (2010). Infants' responses to real humans and representations of humans. *International Journal of Behavioral Development*, *34*, 34–45.
Johnson, M., Senju, A., & Tomalski, P. (2015). The two-process theory of face processing: Modifications based on two decades of data from infants and adults. *Neuroscience and Biobehavioral Reviews*, *50*, 169–179.
Kanakogi, Y., & Itakura, S. (2011). Developmental correspondence between action prediction and motor ability in early infancy. *Nature Communications*, *2*, 341.
Libertus, K., & Needham, A. (2010). Teach to reach: The effects of active versus passive reaching experiences on action and perception. *Vision Research*, *50*, 2750–2757.
Libertus, K., & Needham, A. (2011). Reaching experience increases face preference in 3-month-old infants. *Developmental Science*, *14*, 1355–1364.
Longhi, E., Senna, I., Bolognini, N., Bulf, H., Tagliabue, P., Macchi Cassia, V., & Turati, C. (2015). Discrimination of biomechanically possible and impossible hand movements at birth. *Child Development*, *86*, 632–641.
Loucks, J., & Sommerville, J.A. (2012a). The role of motor experience in understanding action function: The case of the precision grasp. *Child Development*, *83*, 801–809.
Loucks, J., & Sommerville, J.A. (2012b). Developmental changes in the discrimination of dynamic human actions in infancy. *Developmental Science*, *15*, 123–130.
Morita, T., Slaughter, V., Katayama, N., Kitazaki, M., Kakigi, R., & Itakura, S. (2012). Infant and adult perceptions of possible and impossible body movements: An eye-tracking study. *Journal of Experimental Child Psychology*, *113*, 401–414.
Natale, E., Senna, I., Bolognini, N., Quadrelli, E., Addabbo, M., Macchi Cassia, V., & Turati, C. (2014). Predicting others' intention involves motor resonance: EMG evidence from 6- and 9-month-old infants. *Developmental Cognitive Neuroscience*, *7*, 23–29.
Reed, C.L., McGoldrick, J.E., Shackelford, R., & Fidopiastis, C. (2004). Are human bodies represented differently from other animate and inanimate objects? *Visual Cognition*, *11*, 523–550.
Reed, C.L., Stone, V.E., Grubb, J.D., & McGoldrick, J.E. (2006). Turning configural processing upside down: Part and whole body postures. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 73–87.
Reid, V., Belsky, J., & Johnson, M.H. (2005). Infant perception of human action: Toward a developmental cognitive neuroscience of individual differences. *Cognition, Brain, Behavior*, *9*, 35–52.
Sanefuji, W., Ohgami, H., & Hashiya, K. (2008). Detection of the relevant type of locomotion in infancy: Crawlers versus walkers. *Infant Behavior and Development*, *31*, 624–628.
Simion, F., Regolin, L., & Bulf, H. (2008). A predisposition for biological motion in the newborn baby. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 809–813.
Sirigu, A., Grafman, J., Bressler, K., & Sunderland, T. (1991). Multiple representations contribute to body knowledge processing: Evidence from a case of autotopagnosia. *Brain*, *114*, 629–642.
Slaughter, V., & Heron, M. (2004). Origins and early development of human body knowledge. *Monographs of the Society for Research in Child Development*, *69*, 1–102.
Slaughter, V., Heron, M., & Sim, S. (2002). Development of preferences for the human body shape in infancy. *Cognition*, *85*, B71–B81.
Slaughter, V., Heron-Delaney, M., & Christie, T. (2011). Developing expertise in human body perception. In V. Slaughter, & C. Brownell (Eds.), *Early development of body representations* (pp. 81–100). Cambridge, UK: Cambridge University Press.

Slaughter, V., Stone, V.E., & Reed, C. (2004). Perception of faces and bodies–Similar or different? *Current Directions in Psychological Science*, *13*, 219–223.

Sommerville, J.A., Hildebrand, E., & Crane, C.C. (2008). Experience matters: The impact of doing versus watching on infants' subsequent perception of tool use events. *Developmental Psychology*, *44*, 1249–1256.

Sommerville, J.A., Woodward, A.L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition*, *96*, B1–B11.

Southgate, V., Johnson, M.H., & Csibra, G. (2008). Infants attribute goals even to biomechanically impossible actions. *Cognition*, *107*, 1059–1069.

Van der Meer, A.L.H. (1997). Keeping the arm in the limelight: Advanced visual control of arm movements in neonates. *European Journal of Paediatric Neurology*, *1*, 103–108.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Science*, *8*, 266–272.

Wallace, P.S., & Wishaw, I.Q. (2003). Independent digit movements and precision grip patterns in 1–5-month-old human infants: Hand-babbling, including vacuous then self-directed hand and digit movements, precedes targeted reaching. *Neuropsychologia*, *41*, 1912–1918.

Woodward, A.L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, *69*, 1–34.

Yoshida, H., & Smith, L.B. (2008). What's in view for toddlers? Using a head camera to study visual experience. *Infancy*, *13*, 229–248.

Zieber, N., Bhatt, R.S., Hayden, A., Kangas, A., Collins, R., & Bada, H. (2010). Body representation in the first year of life. *Infancy*, *15*, 534–544.

Zieber, N., Kangas, A., Hock, A., & Bhatt, R.S. (2015). Body structure perception in infancy. *Infancy*, *20*, 1–17.