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Visual Cues Generated During Action Facilitate 14-Month-Old Infants' Mental Rotation

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Although action experience has been shown to enhance the development of spatial cognition, the mechanism underlying the effects of action is still unclear. The present research examined the role of visual cues generated during action in promoting infants' mental rotation. We sought to clarify the underlying mechanism by decoupling different aspects of action experience and choosing to manipulate the visual aspect while holding other aspects constant. Fourteen-month-old infants were given opportunities to rotate a cylinder placed on a turntable; the cylinder was decorated with vertical or horizontal stripes. If the effects of action hinge on the quality of visual cues generated during action, infants should benefit more from rotating the cylinder with vertical stripes as they generate richer cues when each stripe moves laterally with the cylinder. As predicted, the infants in the vertical-stripe condition looked significantly longer at an improbable outcome than at a probable outcome of a hidden-rotation event, whereas those in the horizontal-stripe condition looked about equally at the 2 outcomes. The results suggest that the effects of action on mental rotation are derived not from motor experience alone, but from integrating motor and visual experiences.

When infants begin to explore on their own, they can explore and play with objects that were once out of reach, which provides a rich set of information about the world. Developmental psychologists have long emphasized the role of exploratory action on perceptual and cognitive development. Piaget and Inhelder (1948/1956) believed that sensorimotor experience is the root of all basic knowledge about the physical world and specifically highlighted the role of motor activity in learning about objects. Gibson (1988) considered action as a means to acquiring new information: As opportunities for exploration emerge, infants gain and refine their knowledge about the world.

In line with this perspective, the development of spatial perception in infancy has been associated with the emergence of self-locomotion—sitting upright, crawling, and walking—all of which allow infants to explore the world in a new and meaningful way (Acredolo, Adams, & Goodwyn, 1984; Bushnell & Bourdreau, 1993; Campos et al., 2000). Self-locomotion has been shown to influence infants' sensitivity to height (Campos, Bertenthal, & Kermoian, 1992), their ability to search for hidden objects (Bai & Bertenthal, 1992), and their representation of objects. In particular, sitting upright independently contributes to the emergence of perceptual completion (Soska, Adolph, & Johnson, 2010), whereas crawling elevates infants' mental-rotation abilities (Schwarzer, Freitag, & Schum, 2013). In these examples, spatial perception is enhanced

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as infants become better at attending to the object at hand while exploring the world actively, which allows for the integration of information from different modalities.

In the same vein, embodied cognition research stresses the importance of integrating information from multiple modalities when infants develop perceptual skills (Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009) and argues that infants rely on multi-directional flows of information across modalities when learning to perceive objects in the world (Bahrick, Lickliter, & Flom, 2004; Gibson & Pick, 2000; Smith & Gasser, 2005). For example, looking at objects while playing with them helped 10.5-month-old infants track objects by color, whereas being passively shown objects did not (Wilcox, Woods, Chapa, & McCurry, 2007). This finding underscores the importance of visual-motor integration: Visual information generated by one's own action facilitates object tracking more so than information generated by others. Additional work provides further evidence on how the brain processes self-generated and other-generated information differently. For example, auditory information generated by a 5-year-old's own action recruits motor systems and activates different parts of the brain from auditory information generated by others (e.g., James & Bose, 2011; James & Swain, 2011).

More generally, brain research has outlined neural pathways for multisensory integration. For example, the dorsal and ventral pathways, traditionally thought to separately represent "where" and "what" information, are now considered to process information for the purpose of action and object recognition, respectively (e.g., Goodale & Milner, 1992; Harman, Humphrey, & Goodale, 1999; Haxby et al., 1991; James & Atwood, 2009; James & Swain, 2011; Johnson, Mareschal, & Csibra, 2001; Valyear, Culham, Sharif, Westwood, & Goodale, 2006). Furthermore, these pathways are speculated to interact more than traditionally thought, as they supply each other with crucial information. Specifically, the dorsal system specializes in motor-related information, such as information about whether and how an object can be grasped; the ventral system, while specializing in object-identity information, may supply information to the dorsal system for action planning or motor execution (e.g., Almeida, Mahon, & Caramazza, 2010). Through the dorsal–ventral interplay, the development of visual perception goes hand in hand with children's active exploration in the world. Indeed, emerging research on the relations between object play, object recognition, and word learning in childhood provides evidence supporting this view (e.g., James, Jones, Swain, Pereira, & Smith, 2013; James, Swain, Jones, & Smith, 2013; Perone, Madole, & Oakes, 2011; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Street, James, Jones, & Smith, 2011; Teramoto & Riecke, 2010). Despite the growing body of work, the mechanism underlying the action–perception interplay still awaits clarification, and most of this research has focused on toddlerhood and beyond. The present research takes one step further to examine *how* action facilitates infants' spatial perception in the case of mental rotation.

Early work on mental rotation demonstrates that infants as young as 4 months old can track and anticipate the final orientation of an object after it passes and rotates through an occluder (Hespos & Rochat, 1997; Rochat & Hespos, 1996). Further work has shown that 3- to 6-month-olds distinguish a familiar object seen at a novel post-rotation angle from its mirror image. For example, Moore and Johnson (2008) habituated 5-month-olds to an object that rotated back and forth in a 240º arc and tested the infants with a) the same object after being rotated through the unseen 120º arc and b) the mirror image of the object after a similar rotation. Male but not female infants looked longer at b than at a, suggesting that they mentally rotated the representation of the object. However, most mental-rotation research with young infants rarely requires them to initiate the rotation—an ability that is crucial to maintain the three-dimensional representation of the world. To fill this gap, Möhring and Frick (2013) showed 6-month-olds an object being rotated from its original orientation (correct) or its mirror image (incorrect) after it became fully hidden behind an occluder. The occlusion required the infants to initiate mental rotation of the object. The infants given prior hands-on experience with the object distinguished between the correct and incorrect post-rotation images.

Infants' everyday experience with mental rotation is often more complex than telling a single object from its mirror image. Linking the research closer to real-world situations, Frick and Wang (2014) used a task that involved multiple objects and multiple actions. In their task, an experimenter lowered a cover over a toy duck on a turntable and fully hid the duck. Next, the turntable was rotated 90º with the duck remaining covered. Finally, the experimenter lifted the cover to reveal the duck in the correct or incorrect orientation. Whereas the 16-month-olds noticed the incorrect outcome, the 14-month-olds did so only when they were given opportunities, prior to the test, to spin another turntable with a toy turtle placed on it. The 14-month-olds who only observed someone rotating the turtle failed to notice the incorrect outcome.

The present research sought to examine the mechanism underlying the effects of action in Frick and Wang (2014). Rather than viewing action experience holistically, we focused on the fact that action is composed of motor, auditory, and visual experiences and took the decoupling approach by manipulating the visual aspect of action experience while keeping other aspects constant—a method that has not been used in mental-rotation studies.

Previously, Frick and Wang (2014) used a toy turtle in training to present infants with a clear axis of rotation and highly distinguishable features (e.g., the positions of its head, legs, and tail changed as the turtle rotated). The present experiment utilized a cylinder decorated with horizontal or vertical stripes for the following reasons. First, the cylinder generated little distinguishable shape information when being rotated, thus leaving the directionality of the stripes as the main source of perceivable visual cues. Second, horizontal stripes should minimize the amount of visual cues generated as a result of spinning, as the spatial arrangement of the stripes from top to bottom remained the same during rotation, leading viewers to perceive the cylinder as static or to overlook its motion. In contrast, vertical stripes should generate rich visual cues when each stripe moves laterally with the cylinder when it is spun. Vision-for-action research with toddlers (e.g., Street et al., 2011) suggests that when all other facets of action experience are controlled for, the effects of action should be more pronounced when infants are provided with richer visual cues. Therefore, we predicted visual information would mediate the effects of action on mental-rotation performance; as a result, the infants in the vertical-stripe condition should outperform those in the horizontal-stripe condition.

METHOD

Participants

Thirty-two healthy, full-term infants participated (M_{age} = 14 months, 2 days). Half of the infants were randomly assigned to the vertical-stripe condition (M_{age} = 14 months, 5 days; range = 13 months, 2 days to 14 months, 28 days; nine girls), and half were assigned to the horizontal-stripe condition (M_{age} = 14 months, 0 days; range = 13 months, 0 days to 15 months, 3 days; eight girls). The infants were predominantly Caucasian, from middle-class backgrounds, and recruited from birth announcements or local hospitals. Parents were offered travel reimbursement but were not otherwise compensated for their participation. Another nine infants were tested, but their data were excluded due to distraction (n = 6) or fussiness (n = 2) or because the looking time was more than 3 standard deviations from the mean (n = 1).

Apparatus and Stimuli

The apparatus and stimuli were identical to those in Frick and Wang (2014), except that a cylinder, rather than a toy turtle, was used in the training phase wherein the infants rotated the cylinder by a turntable (30 cm in diameter). The cylinder (13.3 cm high, 11.4 cm in diameter) was attached to the center of the turntable, and its side was decorated with vertical or horizontal stripes (see Figure 1 for the settings of the training phase). The stripes (1.9 cm wide) alternated between red and blue.

The stimuli in the test phase included the turntable, a lampshade-shaped black cover, a toy turtle, and a toy duck, as in Frick and Wang (2014). The cover was 17 cm high, 28 cm in diameter at the lower rim, and 9 cm at the top rim. The toy turtle used in the familiarization trials (10 cm × 24 cm) had an orange body with a red shell. Finally, the toy duck used in the test trials (14 cm × 15 cm) was connected to a rod in the apparatus floor to allow the experimenter to adjust its orientation from underneath the apparatus.

All of the events in the test phase were presented in a wooden display box with a large opening; between trials, a fabric-covered frame was lowered to conceal the opening. The back wall of the display box had a small cut-out at the bottom, allowing an experimenter to insert her left hand into the display box to conduct the events. Additionally, a flap on the back wall allowed the experimenter to monitor her movements while staying out of the infant's view.

Procedure

The procedure followed exactly that of Frick and Wang (2014). The infant was seated on the parent's lap at a U-shaped table (see Figure 1). The training phase began when the experimenter removed an occluder to unveil the turntable and then sat across from the infant. The parent was instructed to hold the infant's hand to spin the turntable at first and then let the infant spin it on his or her own. Two observers in an adjacent room behind the one-way mirror tracked the

FIGURE 1 Snapshots of the training phase in the vertical-stripe (left) and the horizontal-stripe (right) conditions.

amount of time the infant spent spinning the turntable (a timer ran until the turntable stopped rotating). The training phase ended when the infant had accumulated 90 s of turntable spinning or when 3 min had elapsed.

Next, the parent and infant were escorted to a separate room to participate in the test phase, which included two familiarization trials and two test trials. The infant was seated on the parent's lap in front of the display box and centered at the turntable, with the infant's eye level approximately 15 cm above the apparatus floor. The parent was instructed to close her eyes and remain neutral during the entire phase. A metronome beat once per second to help the experimenter adhere to the prescribed script. Each trial started after the fabric-covered frame was raised and the infant had looked at the initial static display of stimuli for 2 cumulative seconds.

The first familiarization trial served to introduce the covering movement (Figure 2, top). The experimenter's bare left hand lifted up the cover (1 s), moved it to the left above the turtle (1 s), lowered it over the turtle (2 s), lifted it back up (1 s), and finally returned the cover to its starting position (3 s). The second familiarization trial introduced the turning movement (Figure 2, bottom). The experimenter grasped the front rim of the turntable (1 s) and then rotated it in 90º increments (3 s per increment) counterclockwise. After each 90º turn, the experimenter repositioned her hand to the front rim of the turntable to prevent the infant from associating the orientation of the turtle with hand position.

The test trials combined the movements of the familiarization trials and used the toy duck that had not been seen before (see Figure 3) to limit the possibility that infants became familiar with the toy animal facing a specific direction. When the trial began, the experimenter lifted the cover

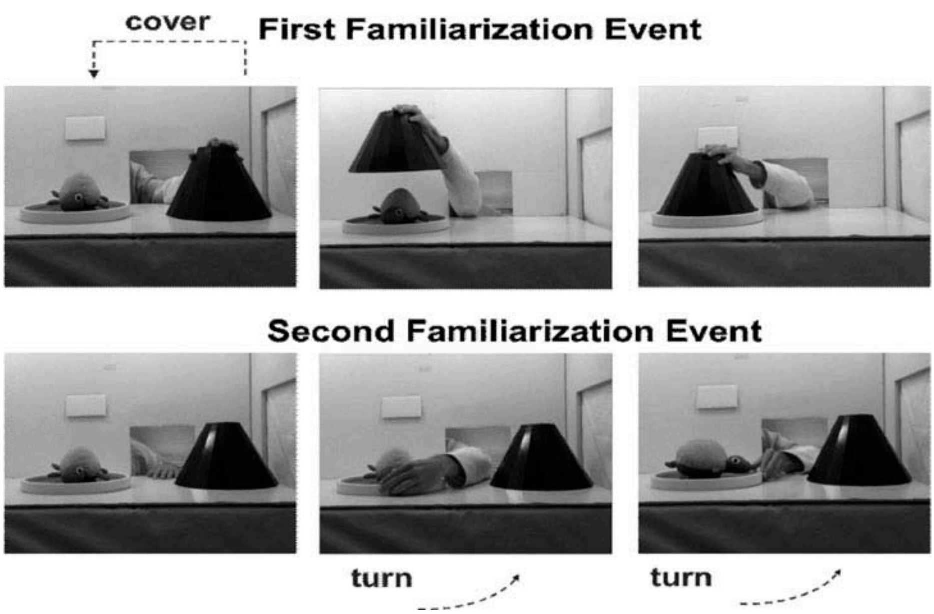

FIGURE 2 Photos of the familiarization events. The first event introduced the covering of the object (top), and the second event introduced the rotation of the turntable (bottom). In the second event, the experimenter rotated the turntable in 90º increments. The sequence in each event was repeated until the trial ended.

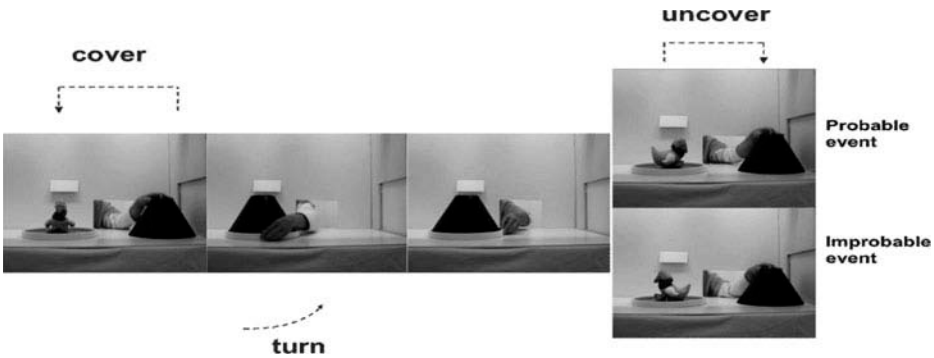

FIGURE 3 Photos of the test events. In the probable event, the duck rotated 90º with the turntable. In the improbable event, the duck rotated 90º in the opposite direction.

(2 s), lowered it over the duck (2 s), turned the turntable 90º counterclockwise (4 s), lifted the cover (2 s), and finally returned the cover to its starting position (2 s). While the experimenter's left hand rotated the turntable, her right hand manipulated a rod from underneath the apparatus to change the orientation of the duck, thereby producing a probable (90º counterclockwise) or an improbable (90º clockwise) outcome. The entire sequence lasted 12 s; the order of test events was counterbalanced across infants.

Two observers, blind to the design and hypotheses, monitored infants' eye gaze during the events through a small hole in the doors at either side of the apparatus. A button on an Xbox controller was connected to a computer for measuring looking times. The input from the primary and typically more experienced observer determined the end of each trial, following the same criteria as in Frick and Wang (2014). Each trial ended a) when the infants looked away from the event for 2 consecutive seconds after having looked at it for at least 8, 12, and 5 cumulative seconds in the first familiarization, the second familiarization, and test trials, respectively; or b) when the infant had looked at the event for 60 cumulative seconds. Interobserver agreement was assessed by dividing each trial into 100-ms segments and calculating the ratio of the number of segments on which the observers agreed to the total number of segments. Interobserver reliability averaged 91.4% across test trials and across 31 infants (SD = 6.5%; only one observer was present for 1 infant).

RESULTS

Preliminary analyses revealed no reliable interactions involving event (probable or improbable) and either order (probable or improbable event first) or sex. Therefore, the data were collapsed across order and sex in subsequent analyses.

First, we verified that infants in the two conditions received an equal amount of hands-on experience rotating the cylinder in the training phase. A paired-samples t test compared the total times during which infants set the cylinder in rotation. The analysis indicated that the total spinning times by the infants in the vertical-stripe condition (M = 80.32, SD = 31.02) were about

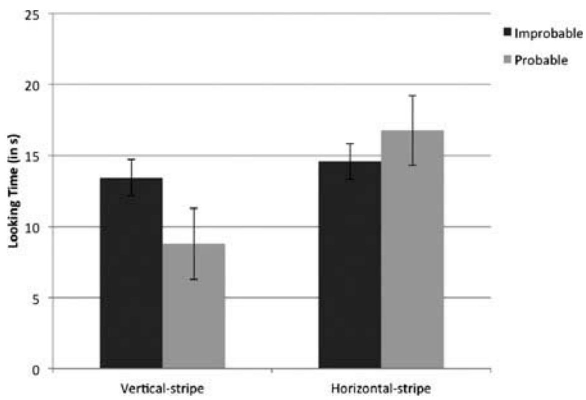

FIGURE 4 Infants' mean looking times at the final paused scene of the test events in the vertical- and horizontal-stripe conditions. Error bars represent standard errors.

the same as those by the infants in the horizontal-stripe condition (M = 79.34, SD = 17.24), $t(26) = 0.10$, $p = .92$.

Next, the infants' looking times at the final paused scene of the probable and improbable events (Figure 4) were compared using a 2 × 2 mixed-model analysis of variance with condition (vertical or horizontal stripe) as a between-subjects factor and event (probable or improbable) as a within-subject factor. The analysis yielded a significant Condition × Event interaction, $F(1, 30) = 5.23$, $p = .029$, $\eta^2 = .15$, suggesting that the looking-time patterns differed across conditions. Planned comparisons indicated that the infants in the vertical-stripe condition looked significantly longer at the improbable (M = 13.43, SD = 5.01) than at the probable (M = 8.78, SD = 3.78) event ($M_{\text{difference}}$ = 4.65, SD = 6.40), $F(1, 30) = 4.88$, $p < .05$, 95% CI [0.35, 8.94], d = 1.05, whereas those in the horizontal-stripe condition looked about equally at the two events (improbable, M = 14.55, SD = 6.41; probable, M = 16.74, SD = 13.27; M difference = –2.19, SD = 10.02), $F(1, 30) = 1.09$, $p > .05$, 95% CI [–6.49, 2.10], d = –0.21.

Finally, we compared the infants' looking times at the familiarization events across conditions, using paired-samples t tests. The analyses indicated that the infants' looking times at the first familiarization event surprisingly yielded a marginal difference (horizontal, M = 54.03, SD = 10.70; vertical, M = 44.38, SD = 16.47), $t(30) = –1.97$, $p = .06$, whereas their looking times at the second familiarization event were about the same (horizontal, M = 36.01, SD = 19.42; vertical, M = 36.71, SD = 15.41), $t(30) = 0.11$, $p = .91$.

DISCUSSION

The present research examined the role of visual information as a contributor to the effects of action on 14-month-olds' ability to track object orientation during a hidden rotation. Previous work (Frick & Wang, 2014) has shown that 14-month-olds' mental rotation is enhanced by prior experience with rotating an object that could provide salient visual cues for the infants to appreciate the consequences of their action on the object. The present experiment examined the mechanism underlying the effects of action by manipulating the quality of visual cues generated during action while keeping other aspects of action experience constant. Although infants in both conditions spent a similar amount of time spinning the turntable in the training phase, only those who acted on the cylinder with vertical stripes detected the improbable outcome of the hidden rotation in the test phase. Despite the fact that the cylinder could not provide easily identifiable points of rotation by its shape, the infants benefited from the visual cues that the vertical stripes generated. In contrast, when provided with only minimal visual cues from horizontal stripes, infants did not benefit from prior experience. Thus, the results provide evidence for the crucial role of visual cues in the mechanism underlying the action effects and suggest that the effects are derived from the integration of visual cues with information from other modalities.

However, there are two noteworthy alternative explanations. First, vertical stripes could be intrinsically more attractive to infants than horizontal stripes, making the vertical group more attentive and ready to detect the improbable outcome. If this were the case, we should have observed differing levels of attention across the two groups during the training phase and the familiarization trials. But the data indicated otherwise. During the training phase, both groups spent a similar amount of time spinning the cylinder, suggesting that the stimuli were of roughly equal interest. Furthermore, the vertical group looked for a marginally *shorter* amount of time than did the horizontal group at the first familiarization event. Although the reason for this marginal difference was unclear, the looking-time pattern spoke against the verticality-preference explanation.

The second alternative interpretation is that the second familiarization event may have induced in infants a transient preference for a particular object orientation. Specifically, the final paused scene of the probable test event implied that a counterclockwise rotation had taken place to the duck while it was hidden. In contrast, the final scene of the improbable test event implied an opposite, clockwise rotation. Prior to the test events, infants saw a counterclockwise rotation (with a different toy) in the second familiarization event, which might make the improbable event more novel than the probable event. Based on this interpretation, we should have observed longer looking times at the improbable event than at the probable event in both conditions. But the data again indicated otherwise. Although infants in the two conditions saw the same familiarization event for a similar amount of time (horizontal, 36.01 s; vertical, 36.71 s), only those who had acted on the vertical-striped cylinder looked longer at the improbable event.

Prior research suggests that bimodal exploration, specifically the pairing of visual and tactile information, leads to deeper encoding of object properties (e.g., Möhring & Frick, 2013; Schwarzer et al., 2013; Wilcox et al., 2007). Our view extends beyond the bimodal perspective by considering action as being composed of experiences across multiple modalities. We believe that integration of information from visual, haptic, auditory modalities, and so forth plays a vital role in promoting spatial perception. In the present experiment, we singled out visual cues generated from one's own actions as an important contributor to the effects of action in spatial perception—a decoupling approach used for the first time in mental-rotation research. Our interpretation for the results is aligned with the existing literature that specifies neural pathways in perception, such as differential responses of the brain to self- and other-generated auditory information (e.g., James & Bose, 2011) and the dorsal stream's specialization in visual information for the purpose of action planning and execution (e.g., Almeida et al., 2010). Most of this existing work has been carried out with older children and adults. Here we provide new behavioral evidence from 14-month-old infants; the finding underscores the role of self-generated visual information during action execution in promoting mental rotation.

The adaptation of the vision-for-action view (e.g., Smith, 2009; Street et al., 2011) separates our research from the previous mental-rotation studies wherein objects (e.g., self-rotating computer-generated images) were shown in contexts that did not engage infants in action planning or execution; this previous work tended to reveal male participants out-performing female participants (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008). Although the lack of sex differences in the present research is not surprising, given that girls may have caught up with boys on spatial development by 14 months (Frick & Wang, 2014; Schwarzer et al., 2013; Soska & Johnson, 2013), it remains an open question as to whether sex differences would still exist if infants are primed to view the images as graspable objects. Such research endeavors will help clarify the role of action planning and execution on sex differences in spatial perception.

Previous research has suggested that action can facilitate perceptual and cognitive development through multiple pathways (e.g., Adolph, 1997; Campos et al., 2000; Eppler, 1995; Gibson, 1988; Oudgenoeg-Paz & Rivière, 2014; Rochat, 1989; Walle & Campos, 2014). It is clear that considering action experience holistically may be leaving valuable information out of the picture. Differentiating various aspects of action experience can be a fruitful approach to understanding developmental pathways, as shown in the present experiment. Following this approach, a potentially interesting extension of the research is to manipulate the motor aspect of action experience—for example, by allowing infants to only spin the turntable with parental assistance and thereby eliminating action control (Gerson & Woodward, 2014; Libertus & Needham, 2010; Lockman, 2000). Another possible extension is to dissociate the motor and visual aspects of the experience—for example, by having infants spin the turntable via a wireless button. The coordination of multisensory information should be hindered when the haptic information infants receive cannot be directly linked to the visual feedback (Bahrick et al., 2004; Ruff, 1989; Soska et al., 2010), and therefore, the effects of action might diminish. Further investigations of these pathways are needed to deepen our understanding about how infants learn to perceive the world through their action.

The present finding extends previous work that examined the benefits of action experience in spatial perception (Campos et al., 2000; Gibson & Pick, 2000) as well as the work that focused more specifically on mental rotation (Frick et al., 2009; Funk, Brugger, & Wilkening, 2005; Krüger & Krist, 2009). It has been suggested that as infants pair visual exploration with manual experience (Eppler, 1995), they form a visual–haptic map of the objects they encounter (Bahrick et al., 2004; Ruff, 1989; Soska et al., 2010). Mapping information in this cross-modal fashion allows infants to direct their attention to relevant information for perception and action planning. Consistent with this perspective, the present finding suggests that infants benefit from action experience through integrating information from visual and motor modalities. Here we highlight the role of visual cues and demonstrate that not all actions are equal: Whether action experience benefits infants' spatial perception depends on the quality of visual cues generated during action.

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