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Volume completion in 4.5-month-old infants

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ABSTRACT

In this study, we examined 4.5-month-old infants' visual completion of self-occluding three-dimensional objects. A previous study on this topic reported that 6-month-old, but not 4-month-old infants extrapolate a convex, symmetric prism from a limited view of its surfaces (Soska & Johnson, 2008). As of yet, studies on the development of amodal completion of three-dimensional, self-occluding objects are scarce. Given 4-month-old infants' abilities to derive three-dimensional shape from a variety of visual cues, three-dimensional amodal completion may well depend on the perceptual strength of three-dimensionality in the stimulus displays. The first experiments (1A and 1B) tested this hypothesis by means of a habituation paradigm and showed that 4.5-month-old infants are indeed able to amodally complete the back of a self-occluding object when sufficient three-dimensional cues are available. Further support for volume completion in 4.5-month-old infants was found in a second experiment, again using a habituation paradigm, that measured perceived connectedness between two visually separated, self-occluding, three-dimensional objects.

1. Introduction

In our daily lives, when looking at the world around us, we generally perceive a stable, coherent world of complete and three-dimensional objects, although the visual input at the retinal level is highly fragmented. For instance, an object becomes visually incomplete when it is partly occluded by another, closer object. Additionally, information about the three-dimensional structure of objects is limited by the perspective of the observer. So, besides objects occluding other objects, single three-dimensional objects also partly occlude themselves. Nevertheless, we effortlessly perceive complete, volumetric objects. The visual process that enables us to experience a scene as containing complete objects, rather than a mosaic of object parts, is called amodal completion (e.g., Michotte, Thines, & Crabbe, 1964). It operates fast (Bruno, Bertamini, & Domini, 1997; De Wit, Bauer, Oostenveld, Fries, & Van Lier, 2006; De Wit & Van Lier, 2002; Gerbino & Salmaso, 1987; Sekuler & Palmer, 1992; Vrins, De Wit, & Van Lier, 2009) and occurs pre-attentively (Rauschenberger & Yantis, 2001; Rensink & Enns, 1998).

In the past few decades, a growing body of research on amodal completion in adults has emerged. Besides testing and developing various models with respect to perceived shape of unspecified parts of partly occluded objects (e.g., Boselie & Wouterlood, 1992; Fantoni, Bertamini, & Gerbino, 2005; Fantoni, Hilger, Gerbino, & Kellman, 2008; Kellman, Garrigan, & Shipley, 2005; Kellman, Garrigan, Shipley, Yin, & Machado, 2005; Kellman & Shipley, 1991; Sekuler, 1994; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995) some studies were also concerned with form perception of self-occluding, three-dimensional objects (e.g., Tse, 1999a,b, 2002; Van Lier, 1999; Van Lier & Wagemans, 1999). Although perhaps phenomenologically less compelling, the unspecified areas of a self-occluding object make object interpretation ambiguous. This ambiguity is solved by amodally "filling-in" the invisible surfaces. This type of amodal completion is sometimes also referred to as volume completion — terms that are used interchangeably in this paper.

Besides research on amodal completion in adults, several studies have also come to focus on the development of this process. Most of the developmental studies on amodal completion show that infants, although differing in some respects from adults, are very well capable of interpreting partly occluded objects within the first 4 months after birth (e.g., De Wit, Vrins, DeJonckheere, & Van Lier, 2008; Johnson, Bremner, Slater, Mason, & Foster, 2002; Kavšek, 2004; Kellman, Gleitman, & Spelke, 1987; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). Interestingly, the age at which infants are found to

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amodally complete self-occluding, three-dimensional objects is not as clear, as the number of studies on this topic of volume completion is still limited. One of these is an experiment by Soska and Johnson (2008), in which 4- and 6-month-old infants were habituated to two sides of what could be a self-occluding, convex prism. Whereas the older age group in a subsequent testing phase dishabituated strongest to a concave interpretation of the object's back, indicating they expected the prism to be convex, the younger age group displayed no preference for either object interpretation. As it seemed, before 6 months of age, infants do not have clear expectations about the shape of the surfaces that form the back of an object. The authors suggested that the emergence of infants' ability to represent complete three-dimensional objects is facilitated by their developing motor skills (i.e., reaching and grasping) and experience with objects in general. This idea was recently confirmed by Soska, Adolph, and Johnson (2010) who investigated amodal completion of a self-occluding prism in a sample of 4.5- to 7.5-month-old infants. They observed that infants with more days of self-sitting experience showed more co-occurring visual and haptic exploration and were also most likely to visually complete a three-dimensional, self-occluding prism.

Notwithstanding a possible role of motor experience in perceptual development, the null-results for 4-month-old infants in Soska and Johnson's (2008) experiment can still be considered as surprising, given research that indicates young infants' proficiency in extracting three-dimensional shape from a variety of visual cues. For example, it has been reported that infants perceive complete three-dimensional structures merely from optic flow well before 4 months of age (Arterberry & Yonas, 2000; Kaufmann-Hayoz, Kaufmann, & Stucki, 1986; Yonas & Arterberry, 1988). Also, other depth cues such as rotation in depth or binocular disparity are known to effectively suggest three-dimensionality in infants of approximately 4 months of age (Johnson, Cohen, Marks, & Johnson, 2003; Kellman, 1984; Yonas, Arterberry, & Granrud, 1987). Although correct perception of three-dimensionality in a specific object scene does not guarantee that a 4-month-old infant also amodally completes the object in question, failing to perceive three-dimensionality in the stimulus display will undoubtedly prevent it.

In case of Soska and Johnson's (2008) study, the 4-month-old infants, who did not amodally complete the self-occluding prism, may not have perceived the stimulus as three-dimensional to begin with. In other words, the stimuli used in their experiments may have been too sparse in terms of visual cues, preventing amodal completion to take place. More generally, it is likely that, when investigating amodal completion of self-occluding objects at this age, a stimulus display that is ‘rich’ in visual cues that disambiguate depth relations between objects or surfaces facilitates three-dimensional representation of the proximal stimulus and possibly also the completion process. The aim of the current experiment is to test this idea.

Therefore, in Experiment 1, we added multiple cues of three-dimensionality to stimuli similar to those of Soska and Johnson's (2008) and tested 4.5-month-old infants' object interpretation. A possible effect of additional visual information on amodal completion would be in line with a constructivist view on amodal completion, as explained below. In Experiment 2, we subsequently tested infants' ability to amodally complete an unfamiliar, three-dimensional object of which a center part was occluded.

2. Experiment 1A

In the literature on development of amodal completion, several researchers take a constructivist point of view (e.g., Johnson, 2001; Johnson & Aslin, 1996; Johnson, Bremner, Slater, & Mason, 2000; Johnson, Davidow, Hall-Haro, & Frank, 2008). This approach proposes an increasingly better integration of different visual cues to go hand in hand with an improvement in directing attention to these relevant aspects of a visual scene. Of particular interest is the threshold model of amodal completion, put forward by Johnson and Aslin (1996), which proposes that amodal completion depends on a variety of visual cues, none of which are sufficient on their own. When there are sufficient cues available to the infant, a threshold is reached and amodal completion takes place. The process of amodal completion is not restricted to perception of partly occluded objects, and the basic idea should also hold for completion of self-occluding, three-dimensional objects.

The following experiment is meant to examine the facilitating effect of a visual display that is rich in depth cues on amodal completion of a self-occluding, volumetric object. For this, the same habituation method and a similar self-occluding object were used as by Soska and Johnson (2008). Importantly, the stimulus displays in our experiment contained more visual depth cues, which enhanced the perceptual three-dimensionality of the scene. Although the experiment does not test the relative effectiveness of specific visual cues encompassed by the threshold model, the overall enhancement of three-dimensionality in the displays is in line with this constructivist approach.

As mentioned above, we created a stimulus similar to the three-dimensional wedge-like shape (or prism) used by Soska and Johnson (2008) and added several visual depth cues to the display. First, in addition to the dotted grid back wall, a similar floor surface was created, which supported the prism. The horizontal dotted grid pattern formed a steady linear perspective that reached until the back wall, providing means to disambiguate the locations in depth of the different corners of the prism. Particularly during habituation, the (back and forth) rotational movement of the prism led to a repeating accretion and deletion of the dotted pattern on the floor surface, indicating the correct position of the prism in space.

Second, because of the added horizontal surface, the virtual light source that lit the scene, would now cast shadows of the prism on the floor. Although past research suggested that infants before the age of 5 months do not use shading cues in determining depth in two-dimensional displays (Granrud, Yonas, & Opland, 1985), more recent studies show that shading can be effective in combination with other cues, such as line junctions that indicate orientation, when infants are as young as 3 months (Bertin & Bhatt, 2006), and possibly with motion at 4 months of age (Johnson et al., 2003).

Third, and also related to the effects of the virtual light source, the surface of the prism was altered to look like clay. Although the latter is not a depth cue as such, the irregularity of the clay-like surface gave rise to subtle color gradients that added noticeably to the impression of three-dimensionality. Producing a clay-like impression involved making the front triangle of the prism irregular, smoothing the prism's edges, and making its surfaces less perfect (Fig. 1). Presented with these visually improved display properties, aimed at disambiguating the three-dimensionality of the scene, it was expected that infants as young as 4.5 months of age would amodally complete the three-dimensional prism.

3. Method

3.1. Participants

The final sample of participants consisted of 32 infants between 4 and 5 months of age (19 girls, 13 boys). Their mean age was 140 days ($SD = 7.0$ days, range 128 to 150 days). In total, a group of 43 participants was tested, but 1 participant was removed from the sample for persistent inattentiveness and 1 for crying. Additionally, 9 infants did not reach the habituation criterion. As being habituated (i.e., a strong decrease in attention for the habituation stimulus) was required to measure dishabituation (i.e., regaining attention for a test display), not having been habituated rendered these infants unsuitable for the experimental group. Consequently, they were also removed from the sample (for a theoretical assessment of the

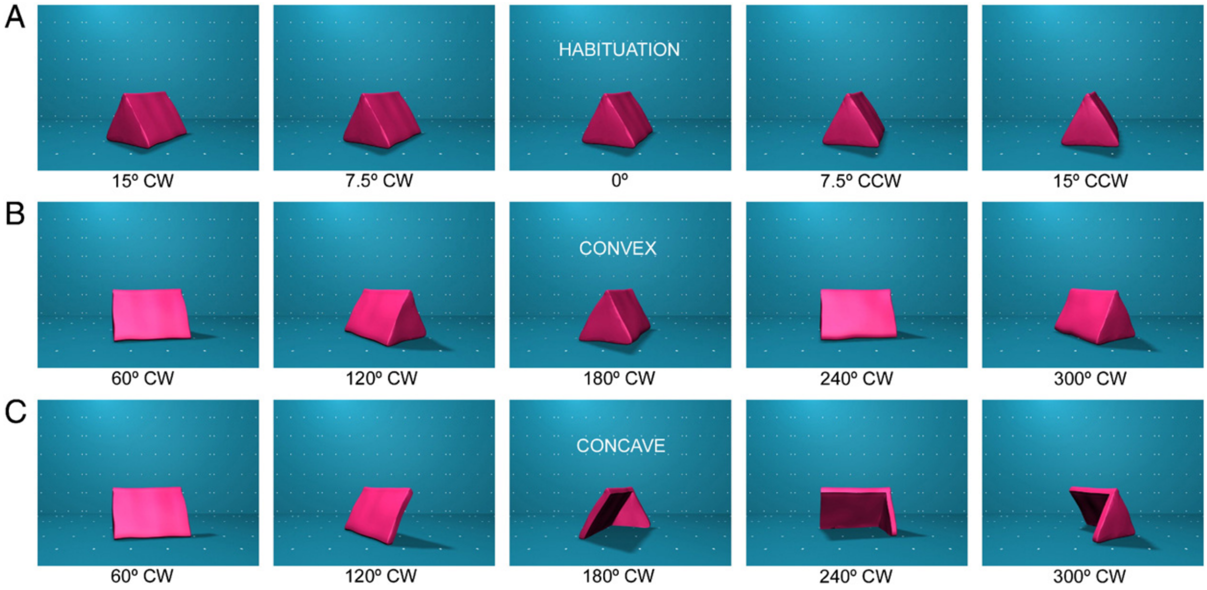

Fig. 1. (A) Different views (in steps of 7.5°) of the limited stimulus rotations in the habituation phase of Experiment 1A. (B and C) Full rotational views (in increments of 60°, clockwise) of the convex and concave test stimuli, respectively. (CW = clockwise, CCW = counter clockwise).

habituation paradigm and what participants to exclude from analysis, see Cohen, 2004).

3.2. Apparatus and stimuli

The stimuli were presented on a large LCD screen (50 inch diagonal) using a Macintosh computer (OS9), which was running a custom habituation program (Cohen, Atkinson, & Chaput, 2004). During the experiment, an observer monitored the infants' gaze by means of a camera and indicated by a button press when the infant's gaze was directed towards the screen. The habituation program recorded the button presses and calculated looking times per trial and the habituation criterion for each infant.

The stimuli were created with three-dimensional Studio Max R2 (1997). First, a floor and back wall were created, which were then 'decorated' with a pattern of white dots to simulate a three-dimensional half-open room. The self-occluding object was a pink prism with an irregular, clay-like surface (Fig. 1A). Vertical shadowing was added to further suggest a three-dimensional configuration. During the habituation phase, the prism rotated 15° in both directions around its vertical axis, taking 4 s to complete a pivot in both directions and return to the center. In the test phase, the object configuration kept rotating in a clockwise direction, each full cycle taking 10 s. The full rotation revealed that the back of the prism was either convex (Fig. 1B) or concave (Fig. 1C).

The objects in the habituation and test phase had a maximum horizontal extent of approximately 12.9° and a maximum vertical extent of approximately 8.8°. To direct the infant's gaze back to the screen after a trial, an attention getter was displayed, which consisted of a large pink ball that bounced up and down, making a salient sound every time it hit the floor.

3.3. Procedure

Infants were placed in an infant seat at a distance of approximately 150 cm from the screen. The experiment started with a habituation phase, in which infants were shown a maximum of 12 trials of the habituation stimulus. A trial ended when the infant looked away for more than 2 s. A trial was considered invalid and run again if the infant looked away within 1 s after onset. The habituation criterion was set to 50% of the mean looking time of the first three trials. If the averaged looking time of three consecutive trials was lower than the habituation criterion, the habituation phase ended. Otherwise, a maximum of 12 trials was presented. The subsequent test phase consisted of six trials, in which the two test stimuli were shown three times in an alternating fashion. The order in which the test displays were presented (concave or convex first) was counterbalanced across participants. Like in the habituation phase, a trial ended when the infant looked away for more than 2 s and was run again when the infant looked for less than 1 s. For each test-trial, looking time was registered.

Half of the participants were randomly assigned to a control experiment, which showed only the test phase. This experiment tested whether infants had a pre-existing preference for one of the test stimuli (i.e., Fig. 1B or C).

Underneath the screen, a camera was hidden behind a black curtain which recorded the infant's face. During the experiment, an observer viewed the infant's face on a monitor behind the experimental setup (invisible to the infant). The observer was oblivious to when the experiment switched from the habituation to the test phase, his task being restricted to pressing a button to indicate if the infant's gaze was directed to the screen. The software by which the experiment was run, calculated the infant's looking time per trial on the basis of the observer's button presses. The infant's face was recorded for later (off-line) coding by a second observer. Interrater scores were obtained by randomly selecting and coding about a third of the recordings (i.e., 12 out of 32). An analysis calculating Pearson's correlation coefficient indicated that interrater reliability was high ($r(70) = .99$, $p < .001$).

4. Results

As mentioned earlier, infants who did not meet the habituation criterion were excluded from the analysis. In concordance with Soska and Johnson (2008), the data (averaged looking times per subject per type of completion), were log-transformed to compensate for skewedness in the looking time distribution (see also Carter Smith, Johnson, & Spelke, 2003; De Wit et al., 2008; Johnson, 2004; Johnson et al., 2003; Termine, Hrynick, Kestenbaum, Gleitman, & Spelke, 1987). As a preliminary analysis revealed no differences in looking times based on the infants' gender or the order of presentation of the test displays, the data were collapsed across these variables in the further analyses.

A factorial mixed ANOVA was performed with the factors Condition (2: experimental vs. control) and Shape (2: convex vs. concave), with Condition being a between-subject factor. There was a significant main effect of Shape ($F(1,30)=4.302$, $p=.047$, $\eta^2=.125$), which was caused by a longer overall looking time (averaged over the experimental and control condition) to the concave stimulus. More importantly, there was a significant interaction of Shape × Condition ($F(1,30)=4.303$, $p=.044$, $\eta^2=.128$), which stemmed from a different pattern in looking time to the test stimuli in the experimental and control condition (see Fig. 2).

Post-hoc paired samples *t*-tests (two-tailed) confirmed that, in the experimental condition, looking time to the concave stimulus was significantly higher than looking time to the convex stimulus ($t(15)=-2.827$, $p=.013$, $d=-.569$). In contrast, looking times to the convex and the concave stimulus did not differ in the control condition ($t(15)=.018$, $p=.986$).

5. Discussion

In Experiment 1A, we tested whether enhanced perceptual three-dimensionality (by means of additional depth cues) would lead 4.5-month-old infants to amodally complete a convex, self-occluding, three-dimensional object. Infants were habituated to a limited view of a prism, similar to that used by Soska and Johnson (2008), yet richer in three-dimensional cues. Subsequently, participants showed a stronger dishabituation response to the concave than to the convex interpretation of the back of the prism. No such preference was shown in the control condition (which did not contain a habituation phase). This contrast suggests that the mental representation of the prism that infants built up during the habituation phase was more similar to the convex than to the concave version of the test stimulus. In other words, infants perceived the self-occluded prism as a convex object, rather than a concave facade of its visible surfaces.

This result is in contrast to Soska and Johnson's (2008) study, in which no particular preference for either object interpretation was found. Plausibly, the 4-month-old infants in their study did not extrapolate a three-dimensional shape from the computer-drawn habituation display. In addition to the Soska et al. (2010) results, which demonstrated that visual completion of such a stimulus is facilitated by higher proficiency in attending to the relevant visual cues (partly attained through motor experience), the results from Experiment 1A suggest that the availability of sufficient visual depth cues can be crucial.

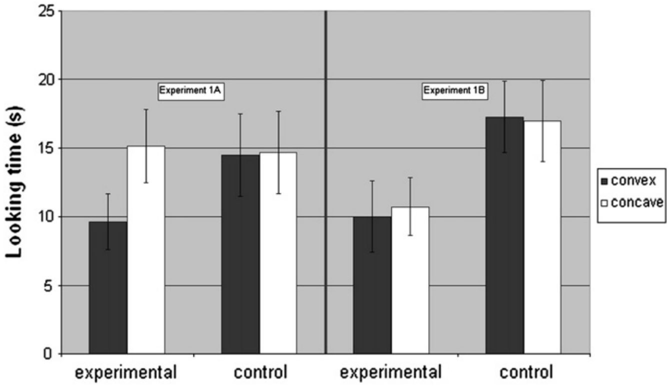

Fig. 2. Looking times (seconds) for each test display (convex and concave) in the experimental and control condition of Experiment 1A (left) and Experiment 1B (right). The error bars represent Standard Errors of the Mean (SEM).

6. Experiment 1B

To corroborate that the results of Experiment 1A were due to the enhanced perceptual three-dimensionality, compared to the poorer three-dimensional displays used by Soska and Johnson (2008), we ran Experiment 1A once more without the additional display properties. In this way, the stimuli closely resembled those used originally by Soska and Johnson (2008).

7. Method

7.1. Participants

The final sample of participants consisted of 32 infants between 4 and 5 months of age (16 girls, 16 boys). Their mean age was 136 days ($SD=9.0$ days, range = 130 to 150 days). In total, a group of 42 participants was tested but 3 participants were removed from the pool for persistent inattentiveness and 1 for crying. Following the same procedure as in Experiment 1A, 6 infants who did not habituate were removed from the sample.

7.2. Apparatus and stimuli

The same equipment and setup was used as in Experiment 1A. The stimuli, now lacking the additional depth cues of Experiment 1A, were more similar to those used by Soska and Johnson (2008). That is, there was no supporting surface and (consequently) the virtual light that was shining down from the top of the configuration cast no shadows, except on the inside surfaces of the concave test stimulus (see Fig. 3). Note that these particular areas were also shaded in the concave test stimulus of Experiment 1A. Further, the object's surfaces in Experiment 1B were perfectly smooth and had sharp edges. The stimuli had a maximum horizontal extent of approximately 12.9° and a maximum vertical extent of approximately 8.8°.

7.3. Procedure

The testing procedure for both the experimental and control condition was the same as in Experiment 1A. Again, 12 of the 32 recordings were randomly selected and coded off-line by a second observer. An analysis calculating Pearson's correlation coefficient showed that interrater reliability was high ($r(70)=.97$, $p<.001$).

8. Results

Like in the previous experiment, the looking time data were log-transformed to compensate for skewedness in the looking time distribution. Also, a preliminary analysis showed no differences in looking times due to the factors gender or order of presentation of the test displays. Consequently, like in Experiment 1A, the data were collapsed across these variables in the further analyses.

A factorial mixed ANOVA was performed with the factors Condition (2: experimental vs. control) and Shape (2: convex vs. concave). Again, Condition was a between-subject factor. There was a main effect of Condition ($F(1,30)=6.011$, $p=.020$, $\eta^2=.167$), caused by longer overall looking times in the control condition than in the experimental condition. In contrast, there was no main effect of Shape ($F(1,30)=.000$, $p=.982$), nor was there an interaction between the two factors ($F(1,30)=.665$, $p=.425$). Fig. 2 depicts the lack of significant differences between the looking times in the experimental condition ($t(15)=-.493$, $p=.629$) and in the control condition ($t(15)=.733$, $p=.475$).

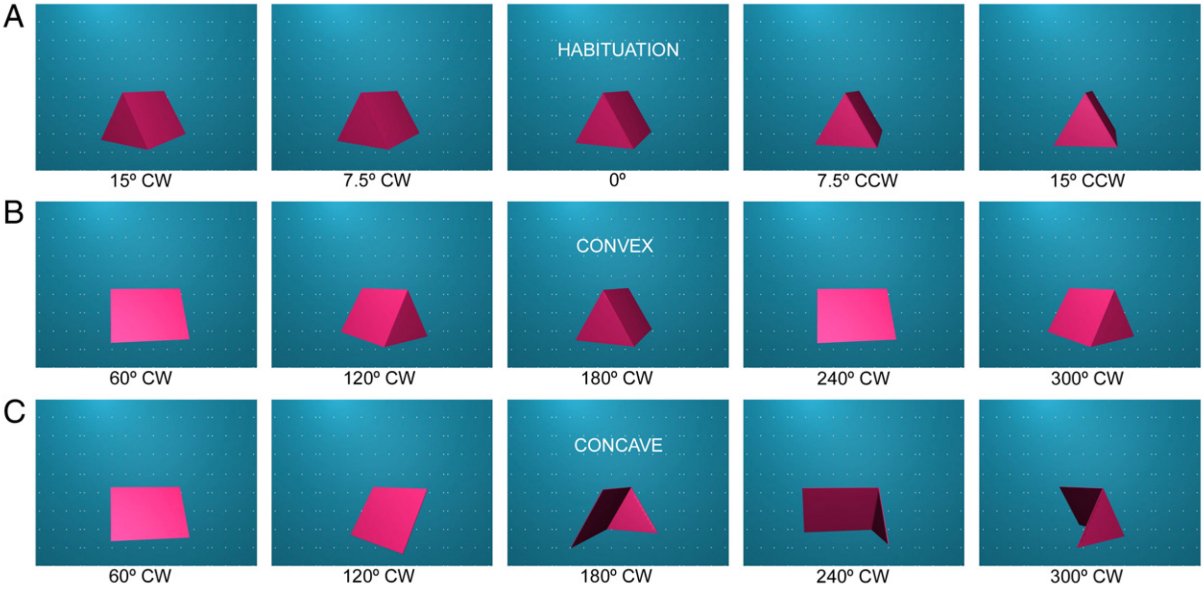

Fig. 3. (A) Different views (in steps of 7.5°) of the limited stimulus rotations in the habituation phase of Experiment 1B. (B and C) Full rotational views (in increments of 60°, clockwise) of the convex and concave test stimuli, respectively. (CW = clockwise, CCW = counter clockwise).

9. Discussion

In Experiment 1B we tested whether the findings of Experiment 1A were indeed related to the additional depth cues, rather than to arbitrary factors, which may have differed in comparison to the Soska and Johnson's (2008) study (e.g., minor differences in stimulus size, background color, room lighting). The results demonstrated that the infants displayed no preference for either object interpretation during the test phase, which is in accord with what Soska and Johnson (2008) found under similar circumstances.

As an alternative explanation of the distinct dishabituation patterns in Experiments 1A and 1B, one might argue that the concave test stimulus in Experiment 1A contained relatively more shaded areas (see Fig. 1) and that the preference for the hollow test stimulus could be caused by this low-level feature. However, a similar influence could then be expected in Experiment 1B (see Fig. 3). Although the total shaded area was smaller than that in Experiment 1A, the shaded areas were almost as large as the object itself and were still rather salient. So, if the novelty response in Experiment 1A would have been due to the darker areas, we would have expected to find a similar novelty response in Experiment 1B. Rather, the results thus imply the need for sufficient visual depth cues (that can effectively suggest three-dimensionality) to attain amodal completion of three-dimensional, self-occluding objects in 4.5-month-old infants.

Importantly, the current experiments show that relatively simple variations in the stimulus display characteristics may determine whether amodal completion is measured in this age group. Although an additional between-subject analysis regarding a possible second order interaction between Experiments 1A and 1B did not reach significance ($F(1,60) = .299$, n.s.), the significant first-order interaction found in Experiment 1A shows that one has to be careful in generalizing the results found by Soska and Johnson (2008). In order to better understand young infants' ability to amodally complete self-occluding objects, future research should explore the various conditions that appeal to this process. Therefore, in the next experiment, we further examined 4.5 month-old infants' perceptual completion of volumetric objects.

10. Experiment 2

Four-month-old infants have repeatedly been shown to amodally complete visually separated object parts in a variety of two-dimensional occlusion displays. Several studies investigated effects of contour properties (e.g., global regularity or contour alignment) using two-dimensional line drawings. The few developmental studies that measured successful amodal completion of three-dimensional occluded objects displayed full 360° rotations (e.g., Johnson et al., 2003; Kellman et al., 1986), leaving no question as to what the back of the object looked like. In Experiment 1A, we have shown that 4.5-month-old infants have expectations about what the unseen back of a three-dimensional object looks like. To further investigate infants' ability to visually complete volumetric objects, we constructed a different stimulus in which a three-dimensional object is centrally occluded by another object, a state of affairs which occurs frequently in the real world.

In contrast to earlier studies, the current experiment investigated amodal completion based primarily on volume interpretation of the two visually separated object parts. Therefore, a three-dimensional occlusion display was created, which consisted of an unfamiliar, clay-like object, wrapped around a yellow cylinder (see Fig. 4). From studies on amodal completion in adults it is known that contour and surface cues, such as collinearity or relatability, suggest connectedness between visually separated object parts, facilitating amodal completion (e.g., Fantoni et al., 2008; Kellman et al., 2005; Kellman & Shipley, 1991). However, as can be seen in Fig. 4, such cues were minimized in the current object configuration — both on a two- and three-dimensional level, from all viewpoints during habituation.[1] Consequently, whether or not infants perceive unity between the two pink blobs on either side of the central cylinder, is contingent on volume completion of these self-occluding object parts. That is, perceiving connectedness would require that the unspecified parts of either piece are perceived as volumetric and as propagating through space, towards the back, and around the cylinder.

If young infants indeed perceive connectedness in this stimulus, it would provide additional evidence with regard to their ability to extrapolate the unseen surfaces of a three-dimensional object from a limited view. After having been habituated to the limited view of

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[1] This particular stimulus is a three-dimensional rendition of a specific occlusion stimulus from a series of studies on amodal completion in adults by Peter Tse (1999a,b). In these studies, Tse demonstrated that amodal completion between visually disconnected surfaces can take place in spite of unrelatable contours and argued that volumetric interpretation (even of pictorial stimuli) is likely to underlie amodal completion.

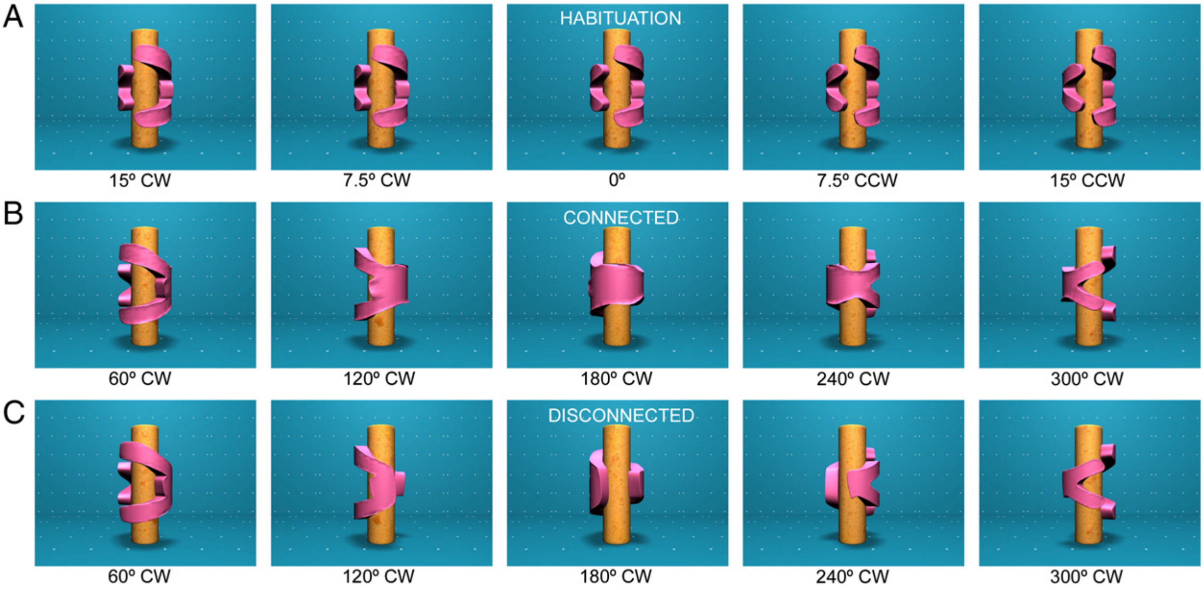

Fig. 4. (A) Different views (in steps of 7.5°) of the limited rotation of the stimulus in the habituation phase of the experimental condition of Experiment 2. (B and C) Full rotational views (in increments of 60°, clockwise) of the connected and disconnected test stimuli, respectively. (CW = clockwise, CCW = counter clockwise).

the stimulus (Fig. 4A), infants should then dishabituate more strongly to a disconnected test stimulus (Fig. 4C) than to a connected test stimulus (Fig. 4B). Otherwise, infants should either dishabituate more strongly to the connected test stimulus or show no preference for either object interpretation.

11. Method

11.1. Participants

The final group of participants consisted of 28 infants between 4 and 5 months of age (11 girls, 17 boys), who were randomly assigned to the experimental or control condition. Their mean age was 142 days ($SD = 8.1$ days; range 122 to 152 days). In total, a group of 43 participants was tested, but 14 infants were removed from the sample for not having reached the habituation criterion, and 1 for persistent inattentiveness.

11.2. Apparatus and stimuli

The same equipment was used as in Experiments 1A and 1B. The test stimuli consisted of a cylindrical pole with slightly tapered edges. The surface of the pole was an irregular yellow-brown pattern to help detecting motion of the pole during rotation. The target object was made to look like a smooth, clay-like substance that was wrapped around the pole (see Fig. 4A). When following the contours of the clay-like object as if projected on a flat surface, the contours of the left and right part of the object were unrelatable. Both the habituation and the test stimuli had a constant vertical extent of approximately 18.9°, and a maximal horizontal extent of approximately 8.8°. The stimuli in the test phase were such that the object parts at the back were either connected (see Fig. 4B) or disconnected (see Fig. 4C). During the habituation phase, the entire object configuration rotated 15° in both directions around the vertical, taking 4 s to complete a pivot in both directions and return to the center. In the test phase, the object configuration kept rotating in a clockwise direction, each full cycle taking 10 s.

In contrast to Experiments 1A and 1B, the control condition in Experiment 2 did contain a habituation phase. The control stimulus during the habituation phase was the same cylindrical pole as in the experimental condition, without the clay-like object. The habituation stimulus in the control condition was included to avoid the following confound: As the control condition was set up to test infants' spontaneous preference for either interpretation of the unfamiliar, clay-like object, their looking behavior should not be influenced by the coinciding presence of a second object (i.e., the cylindrical pole). By first habituating the infants to the empty pole, any measured difference between the two test displays could only be due to the presence of either form of the unfamiliar object.

11.3. Procedure

The testing procedure was the same as in Experiments 1A and 1B, except that the control condition did contain a habituation phase. Like in the previous experiments, about a third of the recordings (i.e., 10 out of 28) were randomly selected and coded by a second observer. Interrater reliability was calculated using a Pearson's correlation coefficient, and turned out to be high ($r(58) = .99$, $p < .001$).

12. Results

Like in Experiments 1A and 1B, the data consisted of looking times for all six test trials, which were averaged for each test stimulus across the three corresponding test trials. Also, looking times were log-transformed to compensate for possible skewedness in the looking time distribution. As preliminary analyses revealed no notable differences between the looking times based on gender and order of presentation of the test display, these factors were excluded from further analyses.

A factorial mixed ANOVA was performed with the factors Condition (2: experimental vs. control) and Completion (2: connected vs. disconnected), with Condition being a between-subject factor. There was a significant interaction of Completion x Condition ($F(1,26) = 6.266$, $p = .013$, $\eta^2 = .194$). This interaction effect stems from different looking time patterns to the test stimuli in the experimental and control condition, which are depicted in Fig. 5. Post-hoc *t*-tests (two-tailed) confirmed that in the experimental condition looking time to the disconnected stimulus was significantly higher than looking time to the connected stimulus ($t(13) =$

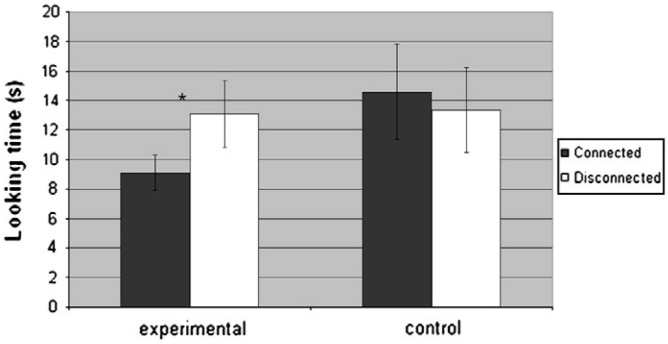

Fig. 5. Looking times (seconds) for each test display (connected and disconnected) in the experimental and control condition of Experiment 2. The error bars represent Standard Errors of the Mean (SEM).

-3.889, $p=.002$, $d=-.522$). In contrast, looking times to these test stimuli did not differ in the control condition ($t(13)=.534$, $p=.602$).

13. Discussion

In this experiment, we tested whether 4.5-month-old infants amodally complete the back of a centrally occluded, three-dimensional object. An unfamiliar, three-dimensional object was created that was presented wrapped around a cylindrical pole. As the contours and surfaces of the distinct object parts were neither collinear nor relatable, and three-dimensional objects are inevitably self-occluding, perception of object unity required a three-dimensional representation of either object part propagating around the pole. The results of the test phase showed that infants dishabituated more strongly to a disconnected test stimulus, which indicates that they perceived the back of the object to be connected.

It might be argued that low level stimulus aspects such as the distribution of colors (stemming from, e.g., the pink blobs and the yellowish cylinder) could also have triggered the differential looking preference after habituation. Notice, however, that such low level stimulus aspects in the habituation stimulus are more similar to the disconnected test stimulus as compared to the connected test stimulus and, in fact, predict another looking preference than the completion interpretation. All in all, we conclude that, the current results provide support for the notion that 4.5-month-old infants amodally complete the unseen backs of (centrally occluded) three-dimensional objects when the stimuli are shown with sufficient 3 day cues.

14. General discussion

In this study, we investigated whether 4.5-month-old infants amodally complete self-occluding, three-dimensional objects. In the past decades, several studies provided evidence for 4-month-old infants' capabilities of perceiving three-dimensional objects from either optic flow, rotation in depth, binocular disparity, or static depth cues (Arterberry & Yonas, 2000; Bhatt & Waters, 1998; Johnson et al., 2003; Kaufmann-Hayoz et al., 1986; Kellman, 1984; Yonas et al., 1987; Yonas & Arterberry, 1988). However, amodal completion of a single, self-occluding three-dimensional object had not been found to occur before 6 months of age (Soska & Johnson, 2008) — although motor experience could facilitate completion (Soska et al., 2010).

In line with a constructivist view of amodal completion (e.g., Johnson & Aslin, 1996), we hypothesized that, given sufficient depth cues which enhance perceptual three-dimensionality, infants as young as 4.5 months would amodally complete the unseen back of a three-dimensional object. Both Experiments 1A and 2 provided evidence for this. That is, the first experiment showed that 4.5-month-old infants perceive a self-occluding, three-dimensional prism as convex. In addition, Experiment 2 showed that infants of the same age, view self-occluding, three-dimensional object parts, abutting either side of a central occluder, as connected.

Note that these experiments measure volume completion in infants and not merely their capability to perceive three-dimensional shape. As already mentioned in the introduction, the non-visible part of a self-occluding object is perceptually ambiguous, appealing to the process of amodal completion. Admittedly, the limited view of the prism displayed in Experiment 1A does yield a fairly stable percept for adult viewers (namely, the convex, rather than the concave shape). Other stimuli, however, may reveal much more ambiguity. For example in Van Lier and Wagemans (1999), pictures of cube-like objects with various indentations were shown to adult observers. The employed sequential matching task revealed that the completion of the previously unseen side strongly depended on the position of the indentations at the visible side and the potential symmetry of the perceived object as a whole. All in all, solving the ambiguity of the unseen side of a three-dimensional object can be considered as an additional step once the stimulus is interpreted as three-dimensional.

Given the results of our experiments, several issues are worth considering. The first concerns the nature of development of visual perception. According to some researchers, the emergence of three-dimensional object perception revolves primarily around picking up kinematic information (e.g., Kellman & Spelke, 1983; Kellman, 1984). Alternatively, three-dimensional object perception is thought to develop in tandem with increased motor skills and experience in object manipulation (e.g., Soska et al., 2010; Soska & Johnson, 2008). In general, 4.5-month-old infants still have relatively little experience with object manipulation. Of course, the current results do not rebut the influence of action experience on perception, as amodal completion at the age of 4.5 months is not fully developed yet. We would, however, like to point out that Soska and Johnson's (2008) null-results can also be explained by a mere perceptual account, as their choices in creating the test-stimuli limited the extent to which their results can be generalized.

Second, as additional depth cues help to interpret occluded three-dimensional objects, amodal completion is likely to depend on a variety of cues, none of which are necessarily sufficient on their own. This is – as pointed out before – in accord with a constructivist view on perceptual development, in which different combinations of cues are presumed to become more and more integrated by the visual (and visuo-attentional) system to form the eventual percept. Still, when it comes to viewpoint generalization, which is closely related to amodally completing self-occluding three-dimensional objects, 4-month-old infants fail when viewing static images (Kellman, 1984). Even in relatively simple, two-dimensional occlusion displays, infants do not perceive object unity until 6 to 8 months when the stimuli are static (Craton, 1996; Kavšek, 2004). This suggests that, although multiple cues are effective in amodal completion, kinematic information does seem of primary importance.

On a final note, to sketch a parallel with amodal completion in adults, it is worth mentioning that effects of unclear or ambiguous depth relations on amodal completion is not a mere typicality of development. Various studies on visual completion in adults have shown that uncertainty about depth may influence the perceived outcome, e.g., dealing with 2D mosaic interpretation vs. 3D occlusion interpretation (Bruno et al., 1997; Rauschenberger, Peterson, Mosca, & Bruno, 2004; Rauschenberger & Yantis, 2001; Sekuler & Palmer, 1992). Not surprisingly, the fact that perceived depth relations strongly influences the outcome of visual completion is found both in models on visual completion in adults (see e.g., Kellman et al., 2005) and infants (e.g., Johnson et al., 2008).

All in all, in contrast to what has been assumed previously, infants amodally complete a three-dimensional, self-occluding object by the age of 4.5 months, when sufficient depth cues are available. This is also the case for three-dimensional, partly occluded objects. Although kinetic cues have repeatedly been shown to be of particular importance for three-dimensional object interpretation, multiple cues appear to be necessary for visual completion around the age of 4 to 5 months.

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