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Evidence of amodal representation of small numbers across visuo-tactile modalities in 5-month-old infants

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Abstract

Two experiments investigated 5-month-old infants' amodal sensitivity to numerical correspondences between sets of objects presented in the tactile and visual modes. A classical cross-modal transfer task from touch to vision was adopted. Infants were first tactually familiarized with two or three different objects presented one by one in their right hand. Then, they were presented with visual displays containing two or three objects. Visual displays were presented successively (Experiment 1) or simultaneously (Experiment 2). In both experiments, results showed that infants looked longer at the visual display which contained a different number of objects from the tactile familiarization phase. Taken together, the results revealed that infants can detect numerical correspondences between a sequence of tactile and visual stimulation, and they strengthen the hypothesis of amodal and abstract representation of small numbers of objects (two or three) across sensory modalities in 5-month-old infants.

Keywords: Infancy; Numerosity; Tactile perception; Intermodal transfer

1. Introduction

A wealth of studies in the last few decades has devoted attention to the investigation of numerical abilities in infants. The current question is whether there is a single system of representation for small and large numbers (Gallistel & Gelman, 1992; Wynn, 1995, 1998) or two distinct representational systems for each type of numbers (Carey, 2001; Feigenson, Dehaene, & Spelke, 2004; Spelke, 2000). According to the first proposal, infants represent number as a single magnitude that is proportional to number. Number is not represented exactly, with the possible exception of

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the first three or four numbers. According to the second proposal, there are two distinct systems of representations. One is a number estimation system similar to the analog-magnitude representation which represents large numerosities. The other system is an object-tracking system that encodes the precise number of individuals in small object arrays (Simon, 1997; Trick & Pylyshyn, 1994; Uller, Carey, Huntley-Fenner, & Klatt, 1999). In this system, infants assign a symbol (a file) to each entity encountered in an array. The number of entities that can be simultaneously represented and stored in memory cannot exceed 3 or 4.

The present study only focuses on the nature of quantity representations of small object arrays. Earlier studies have provided evidence that infants are able to discriminate different small numbers of entities including sets of visual objects (Antell & Keating, 1983; Starkey & Cooper, 1980) of variable size, shape and spatial layout (Strauss & Curtis, 1981), geometrical shapes in motion (van Loosbroek & Smitsman, 1990), dynamical events such as a puppet jumping two or three times (Wynn, 1996), and auditory sequences of two- and three syllable words (Bijeljac-Babic, Bertoncini, & Mehler, 1991). However, the existence of this ability does not allow us to determine whether it results from an abstract representation of the sets or from sensitivity to perceptual features. There is some evidence that infants use such cues rather than number when comparing two quantities (Clearfield & Mix, 1999; Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002). Thus, when numerosity was "pitted" against contour length or total spatial extent, infants discriminated the test displays on the basis of contour length or spatial extent, but not on the basis of number. These findings do not prove that infants are not able to form numerical representations (see for example Feigenson & Carey, 2003; Feigenson, 2005). However, they confirm that sensitivity to continuous variables contributed to infants' performance in many experiments designed to assess sensitivity to number.

A relevant way to rule out this difficulty is to study numerical discrimination in an intermodal task. This idea has already been examined in auditory-visual tasks. Starkey, Spelke, and Gelman (1983, 1990) studied whether infants detect the numerical correspondences between auditory and visual sets. In these situations, infants had to detect numerical information between spatially extended sets of visible objects and temporally extended sets of audible events which did not share any obvious configurational properties. In several experiments, 6- to 8-month-old infants were shown pairs of stimuli consisting of a visual display of either two objects or three objects while hearing either two or three drumbeats at the same time. In another experiment, visual objects and sound were presented successively. In all cases, the infants looked longer at the set of items that matched number of sounds. This result shows that infants have an amodal mechanism for representing small number of entities and suggests that this representation is abstract.

However, subsequent studies did not seem to find the same results as Starkey et al. (1983, 1990). Moore, Benenson, Reznick, Peterson, and Kagan (1987) observed that infants preferred to look at the number of objects that did not correspond to the number of audible sounds. To explain this discrepancy, Starkey et al. (1990) identified two methodological differences. The first difference was the delay between the two trial blocks: In Starkey et al.'s experiments, Block 2 began a few seconds after the end of Block 1 whereas in Moore et al.'s experiment, Block 2 began after a break of several minutes in which the infant was taken out of the testing room experiment. According to these authors, this long break may yield to a shift of preference between Block 1 and Block 2. The second difference concerned the data analysis. Starkey et al. (1990) obtained the same results as their own when they analyzed the Moore et al.'s (1987) data with the same criteria for exclusion of trials used in their experiments. The authors concluded that the two studies were not contradictory and that aspects of methodology influenced the direction of infants' preference in auditory-visual tasks.

Mix, Levine, and Huttenlocher (1997) also failed to replicate Starkey et al's results. In a first experiment, the authors found the same pattern as Moore et al. (1987), even though their method did not differ in the aspects identified by Starkey et al. (1990). Most importantly, in a second experiment, Mix et al. (1997) took into account temporal information that could have been used for discrimination. When the auditory sequences were presented so that rate and duration varied randomly with numerosity, infants did not show a significant preference for either the numerical equivalent or the non-equivalent visual display. Thus, temporal cues seemed to be more salient than numerosities per se in these tasks. According to the authors, infants' performance would be due to a general perceptive preference.

Recently, Kobayashi, Hiraki, Mugitani, and Hasegawa (2004) came out in favour of an amodal interpretation in simple arithmetic operation. The authors suggested that the differences resulting from these studies were due to the experimental situation per se that was extensively abstract and too difficult for infants: There was no natural relationship between the visual sets and the auditory sequences. Using the violation-of-expectation paradigm, the authors proposed a situation in which the visual and auditory stimuli maintain a relationship which makes it possible to associate them more easily than in Starkey et al.'s situation. Infants were first familiarized with sequences of events showing a few objects where the tone was linked to the object. In that way, sounds could be associated to visual objects. Results showed that 5-month-old infants recognize that "1 object + 1 tone = 2 objects" rather than 3, and that "1 object + 2 tones = 3 objects" rather than 2. Thus, infants are able to integrate information about auditory and visual modalities and anticipate the correct or incorrect outcomes of addition operations across sensory modalities.

Another original way to address the question of amodal representation of small numbers would be to investigate cross-modal numerical correspondences between sets of visible and tactile items. To our knowledge, no such experiments have been conducted on infants. This modality is important for number computation because it is well known that children (and even adults) often use their fingers for counting, whatever their culture and their maternal language. The present study explores this question by investigating cross-modal transfer from tactile sets to visible sets of small numbers of objects in 5-month-old infants.

The cross-modal transfer of information from touch to vision consists of two successive phases: a tactile familiarization phase and then a visual test phase. This task is very difficult because it involves a serial mapping process in which information is extracted in a tactual format and transformed into a visual format. Nevertheless, such cross-modal ability has already been shown in 4 and 5-month-old infants in experiments focusing on object unity perception (Streri, Gentaz, Van de Walle, & Spelke, 2004; Streri & Spelke, 1988, 1989; Streri, Spelke, & Rameix, 1993). This data gave evidence that infants can code information in the tactile mode and then perceive the unity of objects in the visual mode despite several differences in size, volume, texture, shape, etc. (for a recent review, see Streri, 2003). These results suggest that continuous variables should not play a role in detection of numerosities in a cross-modal transfer task from touch to vision in infancy. Moreover, this cross-modal ability to transfer shape information from right hand to vision has recently been shown in two studies in human newborns (Streri & Gentaz, 2003, 2004).

In the present study, in both experiments, we used the preferential looking procedure adapted from studies of infant cross-modal perception. Our experiments consisted of a tactile familiarization phase in which infants received two or three objects in their hand followed by a visual test phase. In this visual phase, the objects of each visual display were presented successively in Experiment 1 and simultaneously in Experiment 2. These two modes of object presentation allowed us to examine the potential role of temporal and spatial cues in performance emphasized previously. We hypothesized that if infants have an amodal representation of small numbers of

Fig. 1. Tactile objects used in both experiments.

objects, then they should be able to detect numerical correspondences between a tactile set of different object shapes and a visual display containing the same number of objects, whatever the modes of visual presentation of the objects.

2. Experiment 1

One group of infants received in their right hand two objects successively (2-tactile-object condition) and a second group three objects (3-tactile-object condition). Then, they were shown two visual displays presented in alternation containing two and three objects, respectively. Moreover, the objects of each visual display were presented successively. As a consequence, if infants are able to feel the number of held objects and transfer the numerical information to the visual mode, then a reaction to novelty, i.e. a longer looking time for the non-matching display, was expected.

2.1. Method

2.1.1. Participants

Twenty-four infants (from 4 months and 15 days to 5 months; $M = 4$ months and 25 days) participated in the experiment. The data of eight additional infants were excluded: two due to persistent crying, four due to inattention and two due to experimenter errors.[1]

2.1.2. Objects

Wooden objects consisting of a ring 2.4 cm in diameter and 0.8 cm thick, a cube 1.7 cm of edge, and a sphere 1.9 cm in diameter were used in the 3-tactile-object familiarization condition (see Fig. 1). Their characteristics varied in two dimensions: rectilinear/curvilinear, full shape/shape with a hole. Only the cube and the ring were proposed in the 2-tactile-object familiarization condition as they differed on all these dimensions. We chose to present three different shapes for two reasons: first, a recent study showed that, with heterogeneous arrays of objects, infants are more likely to represent the numerosity of the collections whereas with identical objects arrays, infants are more likely to compute the total continuous extent of the sets (Feigenson, 2005). Secondly, if we had used the same object in the tactual familiarization phase, infants could have assumed they were being handed the same object several times.

To avoid a cross-modal transfer task of object shape, the visual objects did not look like the tactile objects but were composed of some topological and metric characteristics of the three

[1] Twelve infants (4 months and 15 days to 5 months) received the two visual displays but without previous tactile familiarization. Eight infants looked longer at the 3-object display than at the 2-object display. The mean difference of looking times toward the two displays was 7.06 s (ranged from 1 to 21.3 s). 2 infants looked longer at the 2-object display than the 3-object display. The individual differences between looking times for both displays were, respectively, 7.7 and 17.7 s for each infant. Two infants looked equally at both displays. t-test analysis revealed that the preference for the 3-object display ($M = 15.78$ s) versus the 2-object display ($M = 13.16$ s) was not significant ($t(11) = 9.56$, $p = .36$).

Fig. 2. Visual displays presented in Experiment 1.

tactile objects (see Fig. 2). Visual targets displayed a square with a hole in the centre and a circle placed against one of the sides. Each visual target measured 5.9 cm. They were painted red and presented on a white background. In each visual display, the objects were separated by a 11 cm space. Thus, in the 3-object display, the total area was 17.65 cm^2 and in the 2-object display, it was 11.8 cm^2. The total information surface was not equivalent, but several studies showed that this kind of information (size, area, or perimeter) does not influence the occurrence of a cross-modal transfer from touch to vision (Meltzoff & Borton, 1979; Streri & Gentaz, 2003). Moreover, given the physical characteristics of each visual display, it was not possible to present both displays simultaneously. That is the reason why two visual displays (containing two and three objects, respectively) were presented in alternation.

2.1.3. Displays

Each infant sat in a baby chair placed within a large white experimental box facing a white screen, with white side panels that shielded the infant from the surrounding room. During the tactile familiarization phase, a white square cloth was suspended over the infant's body so that it blocked the infant's view of his or her body while leaving the arms free to move. This cloth was removed during the visual test and the white screen was moved revealing each test display. The visual displays were presented in a 40 cm × 40 cm enclosure. Inside the enclosure, a white screen hid the objects. A 68 cm long rail allowed the sliding of the screen to reveal the objects one by one, in a sequential manner. A video camera, positioned just under the visual displays, permitted observation of the infant's hand and body during the tactile familiarization phase, and observation of the infant's head and eyes during the visual test phase.

2.1.4. Procedure

Tactile familiarization began as soon as the infant was seated and the cloth was positioned over his or her body. The experimenter, seated to the right of the infant, successively placed the objects in the infant's right hand. The infant's right hand was chosen because this hand has often been stimulated in the young infant's cross-modal transfer task (see Streri, 1993). Grasp duration of 30 s for each object was proposed. When infants opened their hands, the experimenter prevented the dropping of object by slightly maintaining it. Infants could feel the object shape but not release it. After holding an object, the infant was presented with a different object for another familiarization in the 2-tactile-object condition and a third object in the 3-tactile-object condition. Consequently, the total tactile familiarization duration was either 60 or 90 s according to the conditions and the number of tactile contacts was minimized to one per object (two or three impacts). Twelve infants participated in the 2-tactile-object familiarization phase and twelve in the 3-tactile object familiarization phase.

In the visual test phase, one visual display appeared when the white screen was moved on the rail by the experimenter. The putting in place of a visual display took 3 s: In the 2-object display, the first object appeared and the second appeared 2 s later whereas in the 3-object display, each object was revealed with 1 s interval. The experimenter was warned by a weak noise as soon as the last visual object was presented. The infants' looking times were calculated once the putting in place was ended, i.e. when the whole visual display was visible by infants (two or three objects according to the design). The visual test trial began when the infant looked at the display for at least 1 s and ended when the infant looked away for more than 1 s. At the end of the trial, the screen was closed and the second trial began. Within each tactile group, the two visual displays were presented in alternation during six trials (three test trial pairs) in a counterbalanced order.

Test trial looking times were checked from the video record in a frame-by-frame analysis by the two experimenters (25 frames/s). Neither the visual displays nor the screen that covered the targets between trials appeared on the video record. Timing was handled thanks to a superimposed clock. The two observers therefore coded an infant's looking time in ignorance of the particular display the infant viewed on any given trial. Inter-observer reliability was assessed by checking the total test session looking time recorded for each baby by the two video observers, and by computing the correlation coefficient between their results. Inter-observer reliability was high ($r = .96$).

3. Results and discussion

3.1. General analysis

Fig. 3 presents the mean and standard errors of looking times in the visual test phase in each test trial pair (block) after each tactile familiarization condition.

A preliminary ANOVA on the looking times showed that the factor "order of visual displays" had no effect and did not interact with any other factors (all $p > .25$). Thus, a 2(3-tactile-object

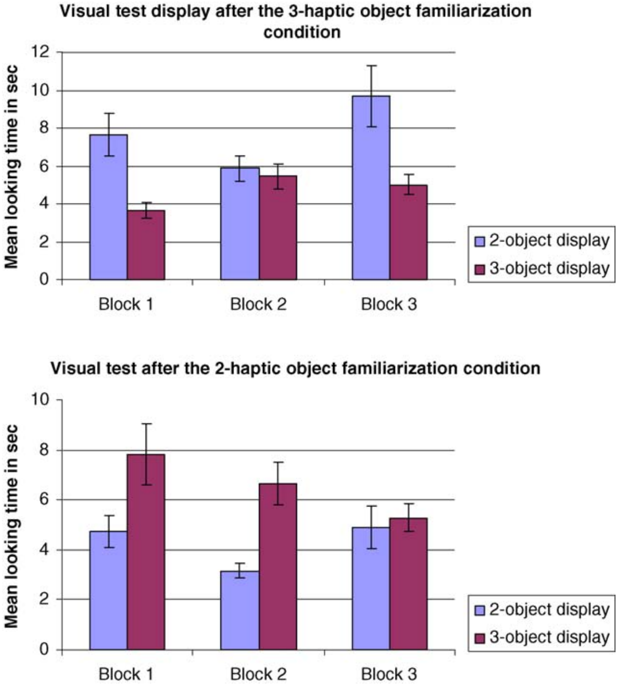

Fig. 3. Mean looking time in seconds (and standard errors) in the test phase as a function of the visual display, the test trial pair (block) and the tactile familiarization phase in Experiment 1.

familiarized or 2-tactile-object familiarized groups) × 3(Visual test trial pairs) × 2(Visual test display: 2- or 3-objects) ANOVA was performed on the looking times with the group as a between-subjects factor and the visual test trial pairs and the visual test display as within-subjects factors.

The interaction between the tactile group and the visual display was significant ($F(1,22) = 16.76$, $p < .001$; this factor explained 69% of the total variance). Pre-planned comparisons revealed that a novelty preference was significant in the 3-tactile-object familiarized group (3-objects = 7.72 and 2-objects = 4.7; $F(1,22) = 10.74$, $p < .005$) and in the 2-tactile-object familiarized group (3-objects = 4.27 and 2-objects = 6.6; $F(1,22) = 6.3$, $p < .05$), with a longer looking time at the novel display than at the familiar display. The group × test trial pair × test stimulus interaction was not significant ($F(2,44) = 0.26$, $p > .25$). All other effects were not significant (all $p > .25$).

Finally, in order to examine whether the results observed could be explained by a visual display effect, we examined a control group in which twelve infants only received the same visual test phase (see footnote 1). The analysis of the looking times revealed no significant difference between the 2-objects visual display and the 3-objects visual display. This means that the results observed in each tactile familiarized group were independent from visual display.

3.2. *Individual analysis*

Individual looking duration (in seconds) for the visual tests revealed that in the group familiarized with the 3-tactile objects, nine infants looked longer at the 2-object display than the 3-object display. The mean difference of looking times toward the two displays was 13.02 s (ranged from 4.9 to 29.7 s, S.D. = 9.93). Results showed that this mean difference was significant (*t*-test, one tailed, $p < .01$). By contrast, three infants looked longer at the 3-object display than at the 2-object display. The individual differences between looking times for both displays were, respectively, 4.1, 2 and 9.5 s for each infant. In the group familiarized with the 2-tactile objects, 10 infants looked longer at the 3-object display than at the 2-object display. The mean difference of looking times toward the two displays was 9.04 s (ranged from 1.8 to 20.8 s, S.D. = 7.18) and was significant ($p < .01$). By contrast, two infants looked longer at the 2-object display than the 3-object display. The individual differences between looking times for both displays were, respectively, 1 and 6.3 s for each infant. In short, 19 infants showed a preference of more than a second for the novel display ($p < .01$, Sign test).

In short, the findings have provided evidence of a numerical cross-modal transfer from touch to vision. However, although the visual durations were calculated when the whole display was visible to the infants, it is possible that the successive presentation of the objects of each visual display influenced two behaviours that enhanced the novelty reaction. In the 3-tactile-object condition, a reaction to novelty could be induced by infant's expectation of a third object that did not appear in the two-object display. In the 2-tactile-object condition, a reaction to novelty could be induced by the infants' surprise to see a third object in the 3-object display that mismatched the tactile stimulation. To examine this interpretation a second experiment was performed in which the objects of each visual display were presented simultaneously.

4. Experiment 2

The main purpose of this experiment was to replicate the previous results with a simultaneous presentation of the objects of each visual display. The same visual shapes that had previously been used were anew presented. But, to focus infants' attention on the whole display, stimuli were constructed to be more easily scanned by them. As previously, if infants are able to feel the number of held objects and transfer the numerical information to the visual mode, then a reaction to novelty was expected.

4.1. Method

4.1.1. Participants

Twenty-four infants from 4 months and 15 days to 5 months ($M = 4$ months and 25 days) were tested. The data of four additional infants were excluded: two due to persistent crying, one due to inattention and 1 due to experimenter errors.

4.1.2. Objects

Tactile objects were the same as in Experiment 1. Visual stimuli (see Fig. 4) displayed the same shapes as those already presented in Experiment 1. However, infants were presented white

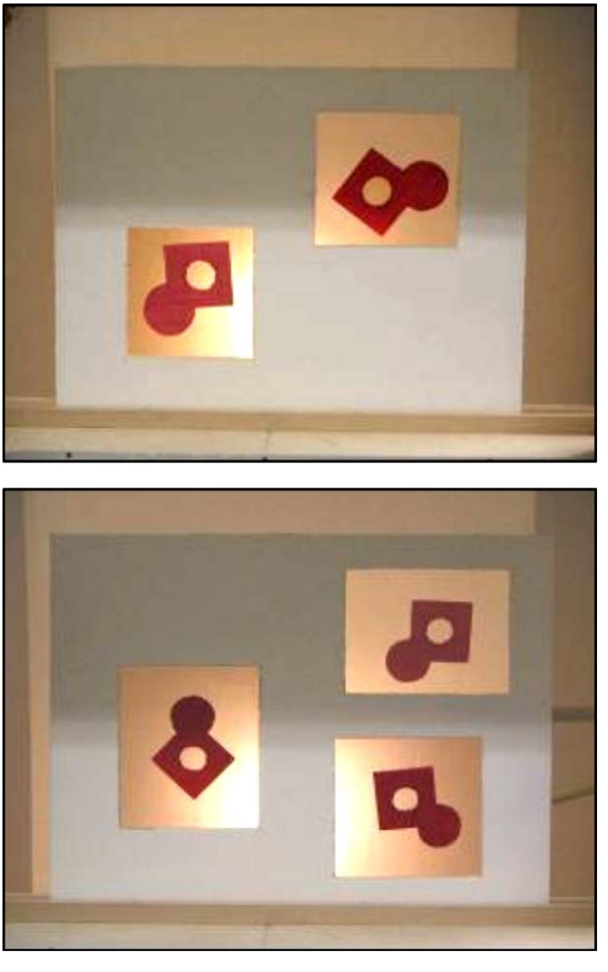

Fig. 4. Visual displays presented in Experiment 2.

boards in which square holes were cut out. The boards were 32.5 cm long and 25 cm wide. Visual flat targets were presented inside the patches in slight movement. In the 2-object display, each target measured 27 cm^2 in area (54 cm^2 for two objects) and in the 3-object display, each object was 18 cm^2 (54 cm^2 for three objects). Thus, the total information was equivalent in both visual displays. As in Experiment 1, given the physical characteristics of each visual display, it was not possible to present both displays simultaneously. That is the reason why two visual displays (containing two and three objects, respectively) were presented in alternation.

4.1.3. Procedure

Design and procedure were the same as in Experiment 1 for the tactile familiarization (i.e. 30 s consecutive holding time per object). Infant sat in a baby chair in front of white curtain that hid the visual display. After the tactile familiarization phase, a second Experimenter parted the curtain to reveal one visual display. The visual test trial began when the infant looked at the display for at least 1 s and ended when the infant looked away for more than 1 s. At the end of the trial, the curtain was closed again and the display was changed. Within each tactile group, the two visual displays were presented in alternation during six trials (three test trial pairs) in a counterbalanced order. Test trial looking times were checked from the video record by the two experimenters. Neither the visual displays nor the curtain that covered a display between trials appeared on the video record. Trial onset was indicated by a shift in the infants' gaze triggered by the opening of the curtain. As soon as the infants looked at the display (generally immediately), timing was handled thanks to a superimposed clock. The two observers therefore coded an infant's looking time in ignorance of the particular display the infant viewed on any given trial. Inter-observer reliability was again high ($r = .96$).

5. Results and discussion

5.1. General analysis

Fig. 5 presents the mean and standard errors of looking times in the visual test phase in each test trial pair (block) after each tactile familiarization condition.

A preliminary ANOVA on the looking times showed that the factor "order of visual displays" had no effect ($p > .17$). Consequently, results were collapsed across order condition. Thus, we conducted a 2(3-tactile-object familiarized or 2-tactile-object familiarized groups) × 3(Visual test trial pairs) × 2(Visual test display: 2- or 3-objects) ANOVA on the looking times with the group as a between-subjects factor and the test trial pairs and the visual test display as within-subjects factors. The interaction between the tactile group and the visual display was significant ($F(1,22) = 30.98$, $p < .00001$; this factor explained 40% of the total variance). Pre-planned comparisons revealed that a novelty preference was significant in the 3-tactile-object familiarized group (3-objects = 10.55 and 2-objects = 13.75; $F(1,22) = 11.48$, $p < .003$) and in the 2-tactile-object familiarized group (3-objects = 11.9 and 2-objects = 7.66; $F(1,22) = 20.10$, $p < .0002$), with a longer looking time at the novel display than at the familiar display. There was also a significant main effect of the test trial pair factor ($F(1.44) = 4.89$, $p < .05$; this factor explained 33% of the total variance), which reflected longer looking times in pair 1 ($M = 13.9$) than in pair 2 ($M = 11.1$) and in pair 2 than in pair 3 ($M = 7.9$). All other interactions were not significant (all $p > .25$).

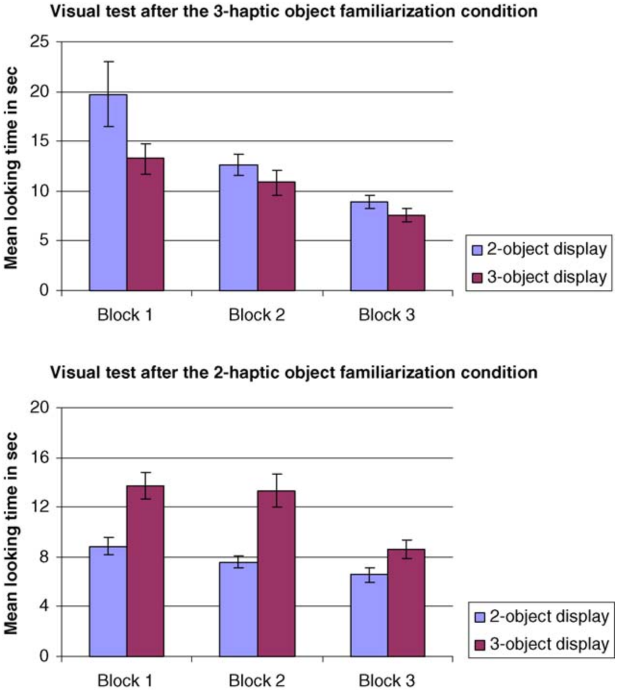

Fig. 5. Mean looking time in seconds (and standard errors) in the test phase as a function of the visual display, the test trial pair (block) and the tactile familiarization phase in Experiment 2.

5.2. Individual analysis

Individual looking duration (in seconds) for the visual tests revealed that in the group familiarized with the 3-tactile objects, 10 infants looked longer at the 2-object display than at the 3-object display. The mean difference of looking times toward the two displays was 11.66 s (ranged from 2.6 to 35.9 s, S.D. = 10). Two infants looked equally toward both visual displays. In the group familiarized with the 2-tactile objects, all the infants looked longer at the 3-object display than at the 2-object display. The mean difference of looking times toward the two displays was 12.73 s (ranged from 2.1 to 34.9 s, S.D. = 9.5). In short, 22 of the 24 infants showed a preference of more than a second for the novel display ($p < .01$, Sign test).

In short, the findings confirmed those observed in Experiment 1 and showed the novelty reaction was not explain by the successive presentation of the objects in each visual display.

5.3. General discussion

The purpose of these two experiments was to investigate 5-month-old infants' amodal sensitivity to numerical correspondences between sets of objects presented in the tactile and visual modes. In both experiments, results showed that $4\frac{1}{2}$ to 5-month-old infants in both conditions of tactile familiarization looked significantly longer at the non-matching display than at the matching display. The findings revealed that infants are able to abstract the number of distinct entities in a tactile sequence, to memorize this information and to compare it with information presented in the visual mode. These findings are obtained with the successive (Experiment 1) or simultaneous (Experiment 2) presentations of the visual objects. This ability is also independent of the intrinsic properties of the objects such as shape and size. Moreover, it is possible that by reducing the number of contacts to one per object, infants would find it difficult to create a clear shape representation of three well-differentiated objects. Consequently, it is more probable that infants have detected a number of events or contacts and not different shapes. This result supports that obtained by Wynn (1996) in 6-month-old infants: in this experiment, infants are able to differentiate 2 vs. 3 events in the visual mode.

Our findings revealed that infants are able to detect the number in a set despite variations in object features (such as shape), modalities (tactile or visual), and mode of presentation (successive or simultaneous). They support Starkey et al. (1983)'s results and shed light on the debate about the nature of numerical knowledge in infancy. Infants, as young as 4 1/2 months, seem to possess a detector of numerosities that operates in an amodal way. This conclusion is also supported by Kobayashi et al.'s research (2004) in an addition operation task across the visual and auditory modalities. However, contrary to Kobayashi et al.'s speculation (2004), evidence for amodal representation does not mean that this ability stems from analog-magnitude representation (cf. Section 1). The object-files model can also account for our results. According to the analog-magnitude model (Gallistel & Gelman, 1992; Wynn, 1995), the tactile familiarization phase would lead to a magnitude corresponding to "2" or "3". During the visual test phase, the two displays would be represented by two different magnitudes, one of which would correspond to that memorized from the tactile familiarization. Infants would thus have reacted to differences in magnitudes. According to the object-files model (Simon, 1997; Uller et al., 1999), infants would have memorized each different shape presented in their hand during the tactile familiarization in the form of "an object and an object" or "an object, an object and another object". With the presentation of the visual displays, they would have carried out a comparison by one to one correspondence between the representation of the tactile and visual entities. Because both models are compatible with our data, others experiments are necessary to specify the nature of the system of representation which underlie infants' behaviour in these numerical cross-modal tasks.

In conclusion, our results showed that young infants are able to detect numerical information in the tactile mode as well as in the visual and auditory modes. Thus, these studies support and strengthen the hypothesis that representation of small numbers of entities is amodal and abstract (Kobayashi et al., 2004; Starkey, Spelke, & Gelman, 1983, 1990). This ability seems independent of the acquisition of language and of culture-specific country.

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