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Numerical Transformations in Five-month-old Human Infants

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We explore numerical abilities in five-month-old infants. Wynn (1992) showed that, when an object is added to or removed from a set of one or two hidden objects, five-month-old infants can infer the result of this transformation. However, in Wynn's experiment, the objects were always placed at the same two locations. Hence, it remained an open question whether infants developed numerical or location-based expectations. To address this question, 56 five-month-old infants were tested using a violation of expectation paradigm with possible (1+1=2 or 2–1=1) and impossible (1+1=1 or 2–1=2) events. One group was tested in conditions identical to Wynn (1992). The other group saw objects being placed on a rotating tray. Since the locations of objects were not predictable, the development of non-numerical, location-based expectations was prevented. Infants in both groups looked longer at numerically impossible events than at the related possible events. These results suggest that infants use a more abstract representation than object location, the numerical nature of which is discussed.

Recent experiments suggest that very young infants, and even newborns, are able to discriminate small sets of items according to their numerosity. Ten- and four-month-old infants have been shown to habituate to a set of two or three dots and to dishabituate when the numerosity changes from two to three or vice versa (Starkey & Cooper, 1980; Strauss & Curtis, 1981). Similar results have been obtained with numerosities of three versus four, but not when larger numerosities

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such as five or six were used (Strauss & Curtis, 1981; but see Treiber & Wilcox, 1984, for a positive result with four vs. six). Newborns have been shown to behave in a similar way with both visual and auditory numerosities (Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1991).

Some of these experiments used only few configurations of items for habituation and dishabituation. Hence the infants could have habituated and dishabituated to each particular spatial configuration of items rather than to numerosity per se. Loosbroek and Smitsman (1991) addressed this question in their study by using small sets of moving objects so that the relative configurations changed continuously. They showed that infant discrimination of small numerosities holds regardless of whether objects are moving or not, and whether partial occlusions occur or not. These results suggest that infants perceive numerosity as though they are endowed with a collection of numerosity detectors that encode numerosity apart from other physical features, at least for small numerosities (Dehaene & Changeux, 1993; Gelman, 1972; Klahr & Wallace, 1973).

Other studies investigated the possibility that numerosity judgements can be transferred from one perceptual modality to the other (e.g. from audition to vision). In the experiments of Starkey, Spelke, and Gelman (1983, 1990), seven-month-old infants appeared to be able to match the numerosity of a set of auditory items to the numerosity of a set of visual items. Moore, Benenson, Reznick, Peterson, and Kagan (1987) presented results that they suggested failed to replicate these experiments. However, Starkey et al. (1990) reanalysed these data and argued that cross-modal matching of numerical information was present in this experiment too. Hence, there is some evidence that numerosity detectors might respond regardless of the sensory modality of input.

Obviously, human adults use many additional properties of numbers (e.g. that numbers form an ordered series, that they can be added or subtracted, etc.). Hence, we may ask whether such properties are part of the infant's core knowledge of the world (Spelke, Breinlinger, Macomber, & Jacobson, 1992), that is, whether they are used to constrain their mental representation of physical events. Wynn (1992a, 1992b) explored infants' ability to use simple arithmetical relations, such as addition and subtraction, to develop expectations about the outcome of physical events. Using the violation of expectation paradigm (Spelke, 1985), she showed that five-month-old infants are able to update a memorised set of hidden, identical objects (one or two) when they see that one object is added or removed from this set (see Simon, Hespos, & Rochat, 1995, for a replication). She interpreted her results as showing that infants have the ability to add and subtract small numerosities.

Unfortunately, Wynn's studies failed to rule out an alternative account that does not involve numerosity. In her study, throughout the pre-test and test phases, the two objects were repeatedly placed at the same two locations behind the screen. For instance, in the 1+1 condition, the first object was always placed at a

fixed location on the left, and the second object was always added at another fixed location on the right. As a result, the infant could develop precise expectations about which locations on the stage should be occupied by objects, and which should not. In the impossible events, they could then detect violations of such location-based expectations. For instance, they could see that a location was empty whereas they expected it to be filled, or that a location was filled when they expected it to be empty. Hence, location-based expectations could explain the observed infants behaviour without resorting to a numerical explanation at all.

Such an explanation is highly plausible because infants at this age are known to possess a refined representation of objects in space. In particular, infants at this age have been shown to attribute different locations to objects that have occupied specific locations previously, and to infer the trajectory of a moving hidden object (Baillargeon, 1992; Baillargeon & DeVos, 1991). They also expect an object to occupy a whole series of intermediate locations when moving continuously from one location to another (e.g. Spelke, Vishton, & Von Hofsten, 1995). The purpose of our experiment was to explore whether Wynn's results would remain true even when the possibilities of such location-based inferences were excluded. In the experiment, 56 five-month-old infants were tested using a violation of expectation paradigm with possible (1+1=2 or 2–1=1) and impossible (1+1=1 or 2–1=2) events. One group was tested in a "fixed" condition, identical to Wynn (1992a), in which the objects always occupied the same two locations. This group could therefore develop location-based expectations. The other group was tested in a "rotating" condition, in which objects were placed on a rotating tray so that their locations were unpredictable. In this group, the development of non-numerical, location-based expectations was therefore prevented. If infants only use a representation of specific locations, they should fail to react to impossible events in the "rotating" condition. However if, as Wynn suggests, infants develop genuinely numerical expectations about addition and subtraction, they should react to impossible events in the "rotating" condition as well as in the "fixed" condition.

Method

Subjects

Participants were 56 healthy, full-term infants ranging in age from 4 months 16 days to 5 months 25 days (mean age: 5 months 10 days). Nineteen additional infants were eliminated from the sample because of experimenter errors (4), or because of fussiness (15). According to reports from parents, infants in the final sample were born at full-term and did not suffer from any known abnormality or illness. Parents were contacted by mail at addresses provided by the legal birth registration of the city of Paris. Volunteers phoned to take appointments and plan their participation. Infants were randomly assigned to one of the four experimental conditions. The four experimental conditions are designated as follows: "fixed 1+1", "fixed 2–1", "rotating 1+1", "rotating 2–1".

Baseline looking times were recorded during a familiarisation pre-test to select in the final statistical sample the subjects who began the test trials with no residual bias for looking at display of one versus two objects. We used the same rejection criterion (see procedure for details) as Wynn (1992a) and Simon et al. (1995). Using this criterion (26 subjects removed) and removing the outlier subjects whose mean looking times were outside the statistical threshold of 2.5 *SD* from the mean (1 subject), 29 infants remained in the final statistical sample, 8 in the "fixed 1+1" condition, and 7 in each of the other conditions. Age and sex were approximately counterbalanced across experimental groups.

Apparatus

The events took place on a 70 cm × 100 cm × 70 cm rectangular wooden stage located at the infant's eye level (see Fig. 1). The display was illuminated by two concealed lamps placed on either side slightly above the stage. The rest of the room was dark. A moveable wooden curtain concealed the entire stage between

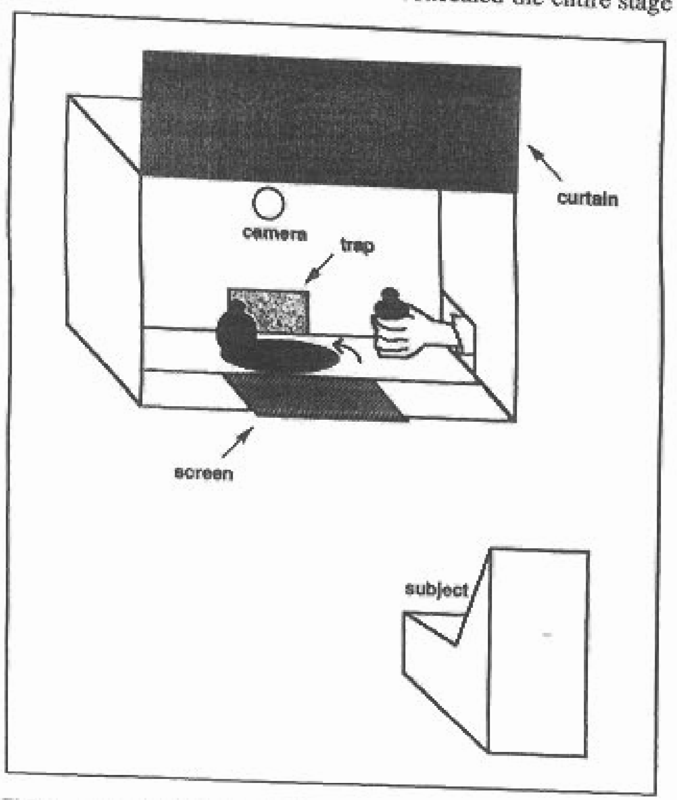

FIG. 1. Schematic diagram of the apparatus as seen from the infant's side.

trials. Objects were introduced on the stage through openings in the lateral walls and were placed on a rotating tray at the centre of the stage. The tray was perfectly round, with no cues that could indicate its angular position. In front of the tray, a motorised, opaque, white screen could be raised to mask the tray and the objects involved in the procedure. A wooden trap in the back wall of the stage behind the tray allowed objects to be removed surreptitiously when the screen was raised. The objects used in these experiments were two identical rigid toys consisting of a pyramid of coloured rings topped with a small rabbit head (approximate dimension: 20 cm × 10 cm). The infants viewed the display from a reclinable seat surrounded by curtains. Infants were at a distance of about 100 cm from the objects. Curtains concealed the room from infants. Parents were asked to sit down behind their infants and to remain still and silent. All events were silent except for a slight humming from the motors of the tray and the screen.

A video camera was placed above the display to videotape the infant's face. A time stamp and a computer signal indicating the onset of the screen lowering were superimposed on each frame of the videotape for later off-line analysis. The experimenter controlled the raising and the lowering of the screen by pressing a button. A second button-press allowed the experimenter to record on-line the subject's fixation by watching on a colour monitor (see recording section for more details).

Procedure

At the start of the experiment, the subject was placed in the seat facing the empty display. The experimenter focused the camera on the infant's face and lowered the curtain to conceal the display. Then the familiarisation pre-test phase of the experiment began.

Familiarisation. In familiarisation trials, one or two objects were placed on the tray and the screen was raised. The trial began with the opening of the wooden curtain. The screen was lowered roughly 1 sec later. One and two object trials were alternated, and order was counterbalanced in each condition. In the "fixed" condition, the tray remained still and the objects were systematically placed at the same location on the tray, one on the left and, when needed, the other on the right (object interval: about 15 cm). In the "rotating" condition, the tray rotated (velocity: about 15 rounds per minute) and the objects were placed on it at various locations. To ensure that the infant could not tell the two objects apart, they were always placed at the same distance and orientation relative to the axis of rotation. The tray was stopped exactly 5 sec. after the screen was lowered.[1] At

[1]In a pilot experiment, the tray was not stopped after the screen was lowered, but this revealed that infant gaze was captured by the perpetual rotation movement: Rotation also involved regular occlusion phenomena between the two objects which moved continuously at different depths of the stage. This rather complex, moving display induced infants to become fussy. We prevented such reactions by automatically stopping the display exactly 5 sec after the screen was lowered.

the end of a trial, the curtain was lowered, concealing the whole display. The next display was prepared, and the subsequent trials began when the curtain was raised.

Familiarisation trials were performed to habituate infants to the whole displays. There were two familiarisation trials in the "fixed" condition and four trials in the "rotating" condition because the moving displays were much more attractive for the infants. Familiarisation trials were also used to record a baseline of the infant looking times for the displays with one or two objects. The baseline data allowed us to select in the final statistical sample the subjects who began the test trials with no residual looking bias for displays of one versus two objects. We used the same criteria as Wynn (1992a) and Simon et al. (1995): We eliminated in the final statistical sample subjects that looked at least 10 sec longer at one display than at the other during familiarisation trials. The exact value of this threshold was irrelevant: all the following significant results remained the same when another value was used (e.g. the same subjects, with the exception of one, were kept when a threshold of 15 sec was used), and the pattern of results remained the same without this threshold.

Test. Test trials then began immediately after these familiarisation trials were completed. Before the beginning of a test trial, the display was empty and the tray rotated in the rotating condition. The curtain was raised and the screen was lowered allowing a full view of the stage. One ("1+1" condition) or two objects ("2–1" condition) were introduced on the right side of the display by the experimenter and placed on the tray in the same manner as in the familiarisation trials. About 2 sec later, the screen was raised, concealing the tray and objects from the infants. In the "1+1" condition, the experimenter introduced the second object on the stage, waited for the infant to look at it, and then placed it on the tray directly behind the screen. In the "2–1" condition, the experimenter introduced his empty hand, waited for the infant to look at it, took one object from behind the screen (the object on the subject's right side in the fixed conditions; the first that arrived on the subject's right side in the rotating conditions), and removed it from the display through the same right opening.

Once these visible manipulations had been made, the experimenter made some hidden changes that remain concealed from the infant's gaze by the screen: In the "1+1" condition, he opened the back trap, introduced his hand behind the screen, and silently removed one object (impossible events) or pretended to remove it (possible events). The trap was then closed and the screen was lowered, revealing either one or two objects. In the "2–1" condition, the experimenter opened the back trap and surreptitiously added one object (impossible event) or pretended to add it (possible events) on the tray behind the screen. The trap was then closed again and the screen was lowered, revealing one or two objects. The duration of the whole manipulation from the beginning of the trial to the lowering of screen was about 20 sec.

In the fixed conditions, the objects were placed at the same fixed locations throughout the experiment. The first object introduced on the stage was always placed on the infant's left side of the tray and the second object on the infant's right side of the tray. Invisible manipulations involved only the object placed on the right. This was done to replicate as closely as possible Wynn's (1992a) original experiment. In the rotating conditions, during the visible manipulations, the objects were always laid down on the moving tray at the fixed location on the right. During the invisible manipulations, the removed object was the first that just arrived in front of the back opening, and the added object was laid down on the moving tray just in front of the back opening. Thus, in the fixed conditions, only two fixed locations were involved; in the rotating conditions, however, the relative configuration formed by the two moving objects changed randomly during each trial and from trial to trial.

The final display in every trial was presented for a minimum of 3 sec and a maximum of 80 sec. Once this time had elapsed, the trial was stopped, the curtain was lowered, and the next trial began. The presentation could be shortened when one of the two following criteria was reached:

1. Infants stopped looking at the display during a continuous time of more than 3 sec. The infant was considered as not looking at the display when it did not look at the objects, the screen, or the tray but looked, for example, at the curtain openings, the camera, or outside the stage.
2. Moreover, the trial was stopped if the cumulated fixation time measured from the beginning of the screen lowering reached 60 sec.

The fixation times used to determine the end of a trial were recorded on-line by the experimenter on the video monitor.

Three impossible and three possible test events were presented to each subject on six alternating trials. The order of trials was counterbalanced across subjects in each group.

Scoring

Off-line recording was used to measure more precisely subject's fixation time for purposes of statistical analysis. The whole experimental session was videotaped with a superimposed timer (1/100e sec) and a computer signal indicating the point when the screen was lowered. Only the subject's face and seat were filmed. An observer reviewed every session off-line to determine the subject's fixation times. The videotape was equipped with a juggle that allowed frame-by-frame viewing. The time interval between two frames was about 0.04 sec. The coding of fixation times was blind; that is, the observer did not know which experimental condition he was coding. As in the on-line recording, an infant was considered to fixate the display when it looked at an object involved in the procedure (the toys, the screen, the tray). The cumulated fixation time in each trial was calculated by adding the times during which the subject fixated the display. This was done until one of the three following criteria was reached:

1. The infant stopped fixating the display for more than 2 sec.
2. The cumulated fixation time reached 60 sec.
3. The end of the trial was over (80 sec).

These values were determined before the experiment and are the ones generally used in this kind of paradigm (e.g. Baillargeon & DeVos, 1991). Note that the on-line threshold to shorten a trial was 3 sec and not 2 sec, to make sure that enough time was recorded and that experimenter evaluation did not interfere with the off-line coding. For estimating the reliability of the scoring, seven subjects were randomly chosen and were coded by two additional observers. Reliability was 91.2%.

Results

Two ANOVAs were separately performed on familiarisation pre-test trials and on test data. In familiarisation trials, mean cumulated looking times were subjected to a $2 \times 2 \times 2$ repeated-measures ANOVA with operation (1+1 vs. 2–1) and condition (fixed vs. rotating) as the between-subjects factors, and final display (one vs. two objects) as the within-subjects factors. This ANOVA revealed no significant main effects or interactions. In particular, there was no main effect of display (one object, $M = 14.7$ sec; two objects, $M = 14.8$ sec), $F(1, 26) = 0.00$, $p > .96$). In accordance with the criteria used to select subjects, there was no residual looking bias for 1 or 2 objects in the pre-test.

In test trials, mean cumulated looking times were subjected to a $2 \times 2 \times 2$ repeated-measures ANOVA with operation (1+1 vs. 2–1) and condition (fixed vs. rotating) as the between-subjects factors, and possibility (1+1=2 or 2–1=1 vs. 1+1=1 or 2–1=2) as the within-subjects factors. The main results of this ANOVA were confirmed using a non-parametric Wilcoxon-Mann-Whitney signed ranks test (Z score). The mean values are shown in Figure 2.

In test trials, the only significant main effect was the possibility effect, $F(1, 25) = 11.60$, $p < .003$, two-tailed, $Z < 0.01$, two-tailed, indicating that infants looked longer at impossible events than possible ones (impossible outcome, $M = 12.2$ sec; possible outcome, $M = 10.0$ sec). Besides this main effect, the ANOVA revealed a significant interaction between possibility and operation, $F(1, 25) = 14.36$, $p < .001$, two-tailed, indicating that the possibility effect is much stronger with "2–1" operation or that a looking bias for two objects tended to appear in test trials (one object after 1+1, $M = 10.4$ sec; two objects after 1+1, $M = 10.8$ sec; one object after 2–1, $M = 9.1$ sec; two objects after 2–1, $M = 14.0$

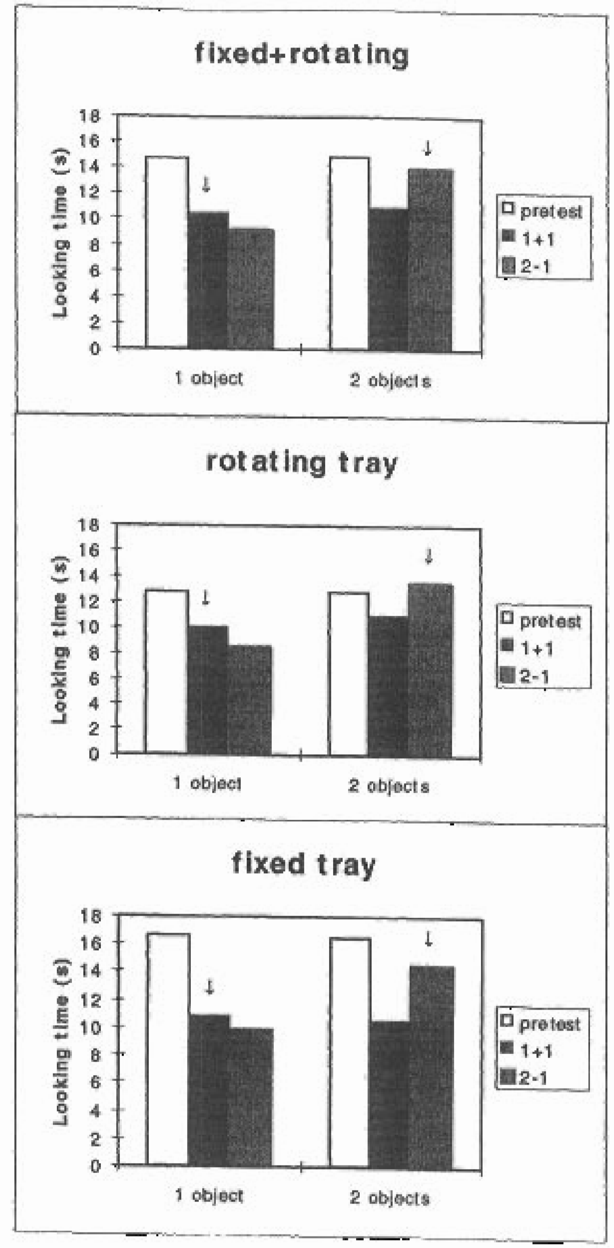

FIG. 2. Infant's mean looking time. Arrows indicate impossible events

sec). A post-hoc analysis revealed a significant effect in the "2–1" condition: infants look much longer at two objects than at one object in this condition, $F(1, 13) = 14.4, p < .003$, two-tailed. However, there was no similar effect of final display in the "1+1" condition.

Although there was no interaction with the conditions fixed versus rotating, we decided to analyse separately the fixed and rotating conditions to examine whether the previous impossibility effect held in the crucial rotating condition. In familiarisation trials, the ANOVA again revealed no significant main effect of interaction.

More importantly, the main effect of possibility for the test trials was again significant in the rotating condition, $F(1, 12) = 7.00$, $p < .022$, two-tailed, $Z < 0.048$, two-tailed. Infants looked longer at numerically impossible events than at possible events (impossible outcome, $M = 11.8$ sec; possible outcome, $M = 9.7$ sec). In the same way, there was again a significant interaction between the possibility and operation factors, $F(1, 12) = 14.36$, $p < .027$, two-tailed, indicating that the possibility effect is stronger in the "2–1" condition than in the "1+1" condition or that a looking bias for two objects in the test trials of the rotating conditions reappeared (one object after 1+1, $M = 10.0$ sec; two objects after 1+1, $M = 10.9$ sec; one object after 2–1, $M = 8.4$ sec; two objects after 2–1, $M = 13.5$ sec). Post-hoc analysis revealed a significant effect of final display in the "2–1, rotating" condition: infants looked longer at two objects than at one object, $F(1, 6) = 15.2, p < .01$, two-tailed. Again, there was no such effect in the "1+1 rotating" condition, $F(1, 6) = 1.03, p > .35$, two-tailed.

In the "fixed" condition, the same ANOVAs revealed the same significant results. There were again no significant main effects or interactions in the pre-test. In test trials, however, infants looked longer at impossible events than at possible ones (main effect of possibility: impossible outcome, $M = 12.7$ sec; possible outcome, $M = 10.2$ sec), $F(1, 13) = 5.26, p < .040$, two-tailed, $Z < 0.056$, two-tailed. There was a marginally significant interaction between the possibility and operation factors, $F(1, 13) = 4.50$, $p = .054$, indicating again that the possibility effect is stronger in the "2–1" condition or that the looking bias for two objects reappeared (one object after 1+1, $M = 10.8$ sec; two objects after 1+1, $M = 10.6$ sec; one object after 2–1, $M = 9.8$ sec; two objects after 2–1, $M = 14.5$ sec). Post-hoc analysis again revealed that infants looked longer at two objects than at one in the "2–1, fixed" condition, $F(1, 6) = 22.97, p < .003$, two-tailed, while there was again no such effect on "1+1, fixed" trials, $F(1, 7) = 0.01, p > .92$.

Discussion

Five-month-old infants looked reliably longer at impossible events than at possible events. Infants also looked significatively longer at two objects than at one object. We will refer to the first effect as the transformation effect and to the second as the complexity effect. Looking times seemingly resulted from the

combination of both effects. When the two effects were in the same direction—that is, looking at two objects versus at one in the "2–1" conditions—infants looked reliably longer at the two-object display than at the one-object display. The complexity effect and the transformation effect tended to add up. Conversely, in the "1+1" condition, the two effects tended to cancel each other and infants looked equally long at the one-object display as at the two-object display.

Several reasons can be adduced to explain the complexity effect. First, a display with two identical objects contains twice as many salient visual features as a display with one object and therefore requires a longer visual exploration (e.g. Bower, 1966). Second, the fact that the two objects are identical may, in itself, enhance the intrinsic interest of the display—for instance, because of its greater symmetry or because it affords a comparison of the two objects.

The main result of this experiment, however, is the transformation effect, which confirms that infants at this age are able to detect whether a numerical transformation is possible or impossible even when location-based inferences are prevented. Our results confirm and extend the results obtained by Wynn (1992a) and Simon et al. (1995). This first indicates that the transformation effect is a robust phenomenon, since our experimental set-up and procedure differed in many respects from those used by these authors even in the fixed condition. In particular, in the present experiments, the duration of the sequence of events in each trial from the beginning to the lowering of the screen (20 sec) was about twice as long as the event duration in Wynn's experiments. Thus, the transformation effect is little affected by the precise timing of the sequences of physical events. In addition, the infants in our experiments tended to look at the display much longer than in Wynn's experiments, because the criteria we used to end a trial were more conservative. This suggests that the transformation effect habituates only little with time.

Our results, like Wynn's, are obtained by rejecting subjects who showed a large bias for looking at one versus two objects, that is, a large complexity effect during the familiarisation trials. When the rejection criteria was relaxed, a post-hoc repeated-measures ANOVA performed on all 56 subjects showed no significant transformation effect, simply because the variance was very high. Interestingly, however, when time was introduced as an additional factor in this ANOVA, the complexity effect interacted linearly with time, indicating that the bias for two objects decreased with time (bias in pre-test, $M = 4.4$ sec; in the first pair of test trials, $M = 5.6$ sec; in the second pair, $M = 1.0$ sec; in the last pair, $M = 0.1$ sec), $F(3, 52) = 4.43, p < .041$, two-tailed. Moreover, in the last pair of test trials, where the bias was negligible, infants tended to look longer at impossible events than at possible regardless of the final display complexity (one object after 1+1, $M = 9.9$ sec; two objects after 1+1, $M = 8.8$ sec; one object after 2–1, $M = 9.8$ sec; two objects after 2–1, $M = 11.2$ sec), although this was not significant, $F(1, 52) = 0.83$, $p < .32$. This suggests that, even in infants who showed a large initial complexity bias, the complexity effect tends to habituate with time, whereas the transformation effect does not.

Second, as infants looked longer at the impossible events than at the possible one, ceteris paribus, this indicates that at least one of their expectations was violated in the impossible events. In the "fixed" condition, which was identical to Wynn's experiment, this violated expectation could be based on location rules, as discussed in the introduction. However, such an explanation could not explain the results of the rotating condition. There were no fixed locations at which the infant could expect objects to be found. The only location-based expectation that the infant could develop was that there should be two objects on the tray in the "1+1" condition and one object on the tray in the "2–1" condition. This, however, constitutes a numerical expectation over and above a location-based one.

Note that the results held only because of a significant difference in looking times to 2–1=1 and 2–1=2 trials. It is therefore of importance to examine whether any alternative explanations could be found for the significant effect in the "2–1" condition. It could be argued, for instance, that infants did not attend to the absolute locations of objects, but to their locations relative to one another. In the "2–1, rotating" condition, they might notice the initial angular separation between the two objects and then expect that, after one object was removed, there should be an empty space at this exact angular separation from the remaining object. However, this explanation cannot account for the surprise that the infants manifested on "2–1=2", because on most such trials this angular expectation was not violated: the second, unexpected object most often did not appear at its previous location relative to the first object.

It could also be argued that this very change in the configuration of the two objects caused the infants to look longer in the "2–1=2" condition. That is, the final display of two objects, because of its new configuration, would look different from the initial display of two objects, and this would be sufficient to trigger prolonged interest in the infants. If it was the case, however, that the infants compared the final display with the initial one, then they should have shown an even higher level of interest for the "2–1=1" condition, in which the final configuration, with only one object, was completely different from the initial configuration of two objects. Hence, explanations based on the relative locations of objects cannot account for the observed results.

Uller and Huntley-Fenner (1995) also investigated the role of location-based inference in Wynn's paradigm. In one condition, which they referred to as the "object-first" condition, they used exactly the same sequence of events as Wynn or we did in the "1+1, fixed" condition: one object was placed on stage, then the screen was raised and a second object was added behind the screen. This sequence was contrasted with another condition, referred to as "screen first", in which the screen was first raised and the first object, and then the second object, were successively added behind it. Wynn's result was again replicated in the "object-

first" condition: infants looked longer at the impossible event (1+1=1) than at the possible event (1+1=2). However, in the "screen-first" condition, eight-month-old infants did not look longer at one object than at two objects. Uller and Huntley-Fenner (1995) then performed an additional experiment similar to the "screen-first" experiment except that two spatially separated screens were used behind which each object was respectively placed. In this last experiment, infants again looked longer at the impossible event than at the possible event.

Uller and Huntley-Fenner's (1995) original explanation of the subjects' failure in the "screen-first" condition was a location-based one: the "screen-first" condition was the only one in which infants did not know the locations of at least one object behind the screen. In the other two conditions, location cues (two separated screens, or one object placed before the screen was raised) were available for infants to draw a location-based inference. Given our data, however, which show that five-month-old infants are able to develop expectations even when object location is unpredictable, it now seems likely that this is not the correct explanation for the difficulty in the "screen-first" condition. A more likely explanation, which is compatible with all current data, is that infants lose track when they have twice to update their memory of the objects present behind a single screen (in the "screen-first" condition), whereas a single update (in the "object-first" condition or ours) or two updates—one for each of two separated screens—would be within their grasp.

This raises the issue of the nature of the memory update that infants perform in our rotating conditions. According to Wynn's (1992a, 1992b) interpretation, which we refer to as the numerical operation model, infants hold a memory of the numerosity of the set of objects behind the screen. They update this numerical memory based on the type of numerical transformation performed. Transformations involving object displacement in the physical world are interpreted in the numerical module as numerical operators (i.e. addition or subtraction). Thus, when one object is introduced or removed, a numerical representation of the object number is changed by the operator "+1" or "–1". Violation of expectation occurs in the rotating impossible events when the expected numerical result of the operation differs from the perceived number of objects.

It seems to us, however, that there is an alternative view which need not grant such abstract knowledge of arithmetic operators to infants. This view is based on the notion of object-file as described in Kahneman, Treisman, and Gibbs (1992). According to this notion, perceived physical objects are assumed to be indexed by internal representations, called object files, which hold a register of various properties of the objects including their location, color, size, etc. Each physical object is indexed by a different file. Slightly different versions of the object-file model have been described elsewhere (e.g. the Finst model: Pylyshyn, 1989), but they are, for current purposes, essentially equivalent to the one described by Kahneman et al. (1992). In the object-file model, some cues induce the opening of new object files, while other cues only lead to an updating of the appropriate parameter in an already opened object file. The key feature needed here is that the rules governing the opening of new object files are based on the principle of spatio-temporal continuity proposed by Spelke et al. (1992): A physical object moves only continuously in space and time from a location to another. Suppose, for instance, that a physical object appears at a novel location—that is, one that is not specified in any currently opened object file. In this situation, a new object file is opened to specify this new location and to refer to the new object. Conversely, when a physical object is perceived to move continuously, the motion cue can be used to update the location parameter specified in the file of this object, so no new object file needs to be opened.

Granting that five-month-old infants possess a functional object-file system may suffice to account for our experimental results. Consider for instance the "1+1, rotating" condition. The first object initially placed on stage is assigned an object file. When the screen is raised, the location parameter of this object file is updated to specify an underdetermined location "somewhere behind the screen". When a second object appears through the lateral stage wall at a new location that is not yet referred to by any file, a new file is opened. And, finally, when the new object is moved continuously and left behind the screen, the location parameter of this second object file can be updated to specify the location "somewhere behind the screen". Hence, after the "1+1" transformation, two object files are opened, both referring to the underdetermined location "somewhere behind the screen". This representation constitutes the content of the infant's expectation about the hidden objects. Violation of this expectation occurs in the impossible 1+1=1 event when no match is found between the opened object files and the perceived objects on the tray—that is, when the *number* of opened object files specifying the location "somewhere behind the screen" mismatches with the *number* of the perceived objects on the tray.

A very similar account can be proposed for the "2–1" transformation. The removal of an object from behind the screen forces the infant to update the location specified by an opened file from "behind the screen" to "beside the screen" (or simply to close this file). Hence, the content of the infant's expectation is now a single opened file with "behind the screen" as its location parameter.

The critical difference between the numerical operation model and the object-file model concerns the nature of the memory representation that is updated when objects are added to or removed from behind the screen: It is a memory of numbers in one case, and a memory of objects in the other. According to the object-file model, there are no calculation procedures in the infant's mind that can take for input two abstract representations of numerosity and produce a third one. There is only the ability to manipulate mental representations of actual physical objects. However, a feature common to both models is that, *in fine*, violations of expectation are always detected by noticing a *numerical* mismatch, either in the number of opened object-files or in the result of a numerical operation. Hence,

both models require granting infants the ability to detect violations of numerical *expectations*—but not the ability to perform numerical *operations*.

In conclusion, our experiments suggest that, beyond drawing inferences about object locations, five-month-old infants are also able to develop numerical expectations about the physical world. This implies that five-month-old infants, over and above perceiving changes in numerosity, use numerical expectations to organise their visual perception. The issue of whether these numerical inferences are the result of calculations within an encapsulated numerical module or of the updating of object files remains open for further research.

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