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Objects are individuals but stuff doesn't count: perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities

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Abstract

Young infants construct models of the world composed of objects tracked through time and occlusion. To date little is known about the degree to which these models are sensitive to the material make-up of the represented individuals. Two experiments probed 8-month-olds' ability to represent different kinds of entities: rigid, cohesive objects, flexible, cohesive objects, and non-rigid, non-cohesive portions of sand. In Experiment 1, infants represented an array of two rigid, cohesive objects hidden behind a single screen, but failed to represent hidden arrays of two flexible objects or two portions of sand. In Experiment 2, entities were hidden behind two screens instead of one, thereby reducing the information processing demands of the task. In that case, infants succeeded in representing arrays of both types of object stimuli, but again failed to represent the portions of sand. It is argued that (1) the processes by which infants individuate and track entities are sensitive to material kind, (2) rigid cohesive objects occupy a privileged status in this system, and (3) early knowledge about objects and substances has a quantificational aspect. © 2002 Published by Elsevier Science B.V.

Keywords: Perceived rigidity and cohesiveness; Infants' representations; Small groups of discrete entities

1. Introduction

Data from a wide variety of sources suggest that infants from 2.5 to 12 months of age can represent small arrays of hidden objects in memory, updating these representations as

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objects are inserted or removed from the array. Although most of the relevant studies have deployed the violation of expectation looking time methodology (Aguiar & Baillargeon, in press; Feigenson, Carey, & Spelke, 2002; Koechlin, Dehaene, & Mehler, 1998; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992), other methods using manual search (Van de Walle, Prevor, & Carey, 2000) and choice between two hidden sets (Feigenson, Carey, & Hauser, 2002) have provided convergent data. In Van de Walle et al. (2000), the dependent measure was persistence of search for hidden objects as a function of the number placed into the box and the number already retrieved, and in Feigenson, Carey, and Spelke (2002) the dependent measure was choice between two containers into which graham crackers had been placed, one at a time. While many of the above studies were originally designed to bear on the question of infant representations of number, they are also relevant to the question of infant object representations and infant capacity to track individuated objects through time and occlusion. That is, they bear on infants' capacity for representations of numerical identity (sameness in the sense of same one) and object permanence.

Indeed, many authors (Carey & Xu, 2001; Chiang & Wynn, 2000; Scholl & Leslie, 1999; Simon, Hespos, & Rochat, 1995; Uller et al., 1999) have suggested that in such tasks the representations that underlie infant performance are object-files (Kahneman, Treisman, & Gibbs, 1992), the very same representations that subserve mid-level object based attention and object tracking in adults. Three considerations support the identification of infant object representations with object files. First, the tracking of small sets of objects by infants is subject to set size limitations similar to those of parallel individuation of objects in multiple object tracking experiments (Feigenson, Carey, & Hauser, 2002; Trick & Pylyshyn, 1994). Second, for young infants spatio-temporal information has a privileged role in computations of object individuation and object tracking, relative to other forms of information, just as is the case in mid-level object based attention (see Carey & Xu, 2001, for a review). Third, manipulations that would be expected to affect the robustness of an object representation in short-term memory affect infant success in the above violation of expectancy tasks (Uller et al., 1999). For instance, the difficulty of a given numerical comparison (1 vs. 2 in Uller et al., 1999; 2 vs. 3 in Baillargeon, Miller & Constantino, 1993) is affected by the number of updates of a short-term memory model that are required to create the final state representation of the objects behind the screen.

Many researchers in the infant literature have challenged the interpretation that the above results concern object representations, object individuation, or representations of numerical identity of objects, suggesting instead that lower level perceptual representations underlie infant performance on these tasks (Bogartz, Shinskey, & Speaker, 1997; Cohen & Marks, in press; Haith & Benson, 1998). On this alternative view, infants encode momentary perceptual arrays, when these are visible, and looking times to subsequent displays are determined by novelty or familiarity preferences relative to previously seen perceptual arrays. For example, Cohen and Marks (in press) suggest that longer looking at the inconsistent outcome in the infant "addition/subtraction" experiments is actually a familiarity preference for an array that is perceptually identical to that seen on the stage floor before the introduction of the screen and the "addition/subtraction" transformation. Such low level perceptual novelty/familiarity accounts deny that infants are forming representations of sets of individuals entities behind the screen and updating these representations as new individuals are inserted or removed. The low level perceptual novelty/familiarity accounts deny that these experiments reflect representations of permanent objects tracked through time and occlusion.

Recent results from Chiang and Wynn (2000) have provided data that challenge any low level perceptual novelty/familiarity account of looking times in the infant "addition/subtraction" studies, at least for 8-month-old infants. They showed that infants' success depended upon the nature of the individuals tracked through time. In several different $1 + 1 = 2$ or 1 experiments, 8-month-olds failed to track stimuli moved behind a screen when those stimuli were first shown to be pyramids of blocks, then decomposed into five separate pieces, and then re-assembled into the original pyramids. The infants succeeded if each pyramid maintained its boundaries throughout the event. These results are not consistent with a low level perceptual novelty/familiarity account. In both conditions (object condition/collection condition) infants encode a pyramid shape on the stage floor that is covered by a screen, and another pyramid shape is then moved behind a second screen. Whether that perceptual array had a history of single bounded coherent object or collection of objects determined success. Chiang and Wynn concluded that success depended upon individuation and object tracking; the object tracking system is well named; it tracks cohesive *objects* but not non-cohesive entities like collections of objects, at least under the experimental conditions of the infant "addition/subtraction" experiments at 8 months of age.

Chiang and Wynn's experiments raise the question of *which* individuals can be tracked through time and occlusion. The stimuli that infants failed to track in the Chiang and Wynn (2000) experiments had two features: non-cohesion[1] and non-rigidity. The pyramids that were decomposed into five distinct blocks (non-cohesion) also failed to maintain a constant shape (non-rigidity). It is plausible that non-cohesion and non-rigidity could each affect probability of success in these studies. Non-cohesion may lead to failure because non-cohesion interferes with individuation and tracing of numerical identity. When an individual falls apart, which part is the *same one* as the original? Relatedly, if the mid-level object based attention system represents *objects*, then non-cohesion may lead to failure because non-cohesive entities violate spatio-temporal conditions of objecthood. Non-rigidity may lead to failure because the processes that build representations of individuals seen disappearing behind a screen may attempt to build an imagistic representation of them and non-rigidity makes such prediction difficult. Motions of non-rigid

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[1] Cohesiveness vs. non-cohesiveness distinguishes not only single objects from collections of objects, but also objects from non-solid substances. The distinction between object kinds and non-solid substance kinds has quantificational implications in the world's languages. The nominal systems of many languages make a principled distinction between terms that may be pluralized and which refer to entities that may be directly counted (count nouns; in English we may say "three dogs"), and those terms that may not be pluralized and which refer to entities that cannot be directly counted (mass nouns; in English we may not say *"three sands"). Not all languages mark the count/mass distinction, and even among those that do, there is cross-linguistic variation in which entities are lexicalized as count nouns and which as mass nouns (see Lucy, 1992 for a review of the cross-linguistic typologies). However, within languages that mark the distinction, a cross-linguistic universal is that non-solid, non-cohesive materials such as liquids, powders, and gels are labeled using mass nouns. In the world's languages, such entities are universally construed as non-individuated; individuation requires measure words or form classifiers (e.g. two *cups* of sand, two *piles* of sand, etc.). Adults appear to naturally construe materials such as sand and water as non-individuated.

entities that change shape through time are perceptually more complex than motions of rigid objects, and the infant may have difficulty tracing numerical identity through shape changes.

The two accounts of Chiang and Wynn's results – *non-rigidity* making it difficult for the infant to keep track of individual pyramids that change shape over time or *non-cohesiveness* introducing ambiguity concerning what the individuals are – are distinguished from low level perceptual accounts, for both of these accounts assume that infants are tracking individuals through time and occlusion. Still, an explanation in terms of cohesiveness is in turn very different from one in terms of non-rigidity, for only the former interprets success or failure as a function of a principled distinction between representations of individuals (objects) and non-individuals (collections).

The present studies begin to explore the effects of non-rigidity apart from non-cohesiveness, by contrasting infants' performance in a $1 + 1 = 2$ or 1 event when the entities are rigid objects, flexible objects, and sand. Non-solid substances such as sand are both non-cohesive and non-rigid as they move through space. If non-cohesiveness or non-rigidity accounts for the failure in the Chiang and Wynn (2000) studies, then 8-month-old infants should also fail to establish models that respect the number of individual portions of sand in these events. If non-rigidity, per se, interferes with object tracking, then infants should have more difficulty tracking non-rigid than rigid objects. If non-cohesiveness interferes with individuation and tracing numerical identity above and beyond the difficulty imposed by non-rigidity, then infants should have even greater difficulty tracking portions of a non-solid, non-cohesive entity, such as sand, in such events.

In the following experiments, as in Chiang and Wynn's studies, to ensure that any differences across conditions are not due to perceptual differences in the static arrays, the rigid objects and sand piles were designed to be physically *identical* from a low level perceptual perspective when at rest. The flexible objects were designed to be as similar to them as possible. Thus, these studies also bear on some of the low level perceptual novelty/familiarity accounts, which would predict similar patterns of success or failure across all conditions, because the infants are shown identical or nearly identical sequences of static arrays on the stage floor during each condition.

2. Experiment 1[2]

2.1. Method

2.1.1. Participants

Forty-six healthy, full-term infants participated in Experiment 1, 26 boys and 20 girls. Their mean age was 8 months and 5 days (SD 12 days). Four additional infants were excluded due to fussiness, experimenter error, or equipment failure. Each infant was randomly assigned to one of three stimulus groups: rigid object, $n = 16$; flexible object,

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[2] The rigid object data in Experiment 1 were previously published (see the object-first condition of Uller et al., 1999).

$n = 14$; or sand, $n = 16$. Infants' names were retrieved from birth records in the Greater Boston area and from commercial lists in New York City. Parents were contacted by letter and by follow-up phone calls. In compensation for participation families received token gifts, such as cups, bibs, or T-shirts.

2.1.2. Stimuli

Three types of stimuli were used: a rigid object, a flexible object, and a small portion of sand. The stimuli were matched as closely as possible so that none would appear to be more interesting than the others when resting on the stage floor. The rigid object was pile-shaped, and its surface was coated in sand. When resting on a flat surface the rigid object looked exactly like a pile of sand. A piece of string was attached to the top center of the rigid object, thereby allowing it to be raised and lowered as a free standing whole; once it was lifted adults perceived it as a rigid, cohesive entity. The flexible object was cohesive but non-rigid. It was made of a soft, semi-solid material (the children's toy, GAK) and it was covered by cloth that roughly matched the sand in texture and color. The flexible object appeared to occupy the same volume as the rigid object and the pile of sand when configured in a pyramidical shape on a flat surface, but it could be placed in other configurations as well. The sand was poured into a small pile on the stage floor.

The rigid object stimulus was roughly the shape of a flattened cone. It measured 15 cm in diameter at the base and 4.5 cm high at the center. The rigid object maintained its pile shape during the whole lowering event. The flexible object was presented in the experimenter's hand, folded into a rectangle, then dangled in a straight line, and then placed on the stage floor in a roughly pyramidical shape. The sand was poured from a transparent cup into a pile of nearly identical shape and dimensions to the objects. The flexible object and the sand each assumed three shapes during the lowering/pouring events (sand: in cup, straight line during pouring, pile on floor; flexible object: rectangle in hand, straight line during lowering, pyramid on floor).

2.1.3. Setup

The experimental events took place in a stage-like display measuring 38 cm high × 88 cm wide × 34 cm deep; this display was raised 100 cm from ground level. A black felt backdrop was positioned behind the display area to hide the observers and the experimenters from the infants. Attached to the front of the stage floor, there was an 88 cm wide × 17 cm high screen that could be raised to occlude the lower half of the display. During the experiment the lab was darkened, but the display was illuminated. A hidden video camera was mounted underneath the display area and used to record the infant's face during the experiment.

Each infant sat in a high chair facing the display with its head about 70 cm away and its eyes slightly above the display floor level. Parents sat to their infant's left, and faced away from the display. Parents were instructed to interact with their infant as little as possible and not to turn to look at the display.

Trained observers recorded the infants' looking times. Observers worked in pairs consisting of one highly experienced primary observer and one secondary observer. Primary observers recorded their data during the experiment, whereas the secondary observers recorded looking time from a videotaped record of the infant's face. To ensure unbiased data, observers were not informed about the details of the experiment. The primary observer was blind as to stimulus type and outcome, and the secondary observer was blind to the experiment the infant looking times were from, and thus to stimulus type and outcome.

2.1.4. Procedure

Each condition consisted of three phases: (1) a tactile exposure phase, in which infants were introduced to the stimulus; (2) baseline trials, which introduced infants to the stage, the lowering events and the screens, and which established baseline preferences between the two outcome displays; and (3) the test trials. We describe the rigid object condition first, and then note how the other two conditions differed from it.

2.1.4.1. Rigid object condition

2.1.4.1.1. Tactile exposure Infants were given a chance to manipulate the object stimulus. The experimenter held the rigid object by its string for the infant to see; then he walked towards the infant's high chair and lowered the object onto the high chair tray. Infants often grasped the object spontaneously. Any who did not were prompted by their parent to manipulate the object. Each infant in the rigid object condition handled an object for 30 s.

2.1.4.1.2. Baseline trials There were two pairs of baseline trials. For the first pair, the entire trial took place in full view. During the second pair, a screen partially occluded the display floor as the objects were lowered. Each pair of baseline trials consisted of a one-object outcome trial and a two-object outcome trial.

During the one-object trial in the "full view" pair, the object was slowly lowered onto the display floor. It paused briefly in mid-trajectory before landing. This 5 s pause corresponded to the time sand was poured from a measuring cup in the sand condition and to the time the flexible object was dangled in a straight-line configuration in the flexible object condition. The infant's looking time to the object at rest was recorded. In the two-object trial, the two objects were lowered simultaneously onto the display floor in full view. The objects paused in mid-trajectory just as in the single object case.

The second pair of baseline trials was similar to the first pair, except that the objects were lowered behind the screen. Participants were first shown that the display floor was empty; then the screen was raised into place. The object was lowered behind the screen until it was partly visible and partly hidden, just as a stream of sand falling behind a screen could be partly visible and partly hidden and just as the flexible object in its line configuration could be partly visible and partly hidden. After a 5 s pause, it was lowered all the way behind the screen onto the display floor. After that, the screen was removed and the infant's looking time at the display was measured. In the two-object trial, the empty display area was shown and then hidden by the screen; then two objects were lowered simultaneously towards the display floor. On the way down the two objects were shown partly hidden during a pause in the lowering, and then lowered completely. Afterwards, the screen was removed to reveal both objects side by side.

There were a total of four baseline trials. These trials alternated between one- and two-object outcomes in two possible orders (one-two-two-one or two-one-one-two). Order and the side of the display floor to which the single object was lowered were counterbalanced.

2.1.4.1.3. Test trials Six test trials immediately followed the baseline trials. For each test trial, participants were first shown the empty display area; then, an object was introduced and lowered onto one side of the display, with a 5 s pause in the middle of the lowering event. Next, the screen was raised into position to hide that object. After the screen was in place, a second object was introduced on the other side of the display and lowered behind the screen onto the display floor, pausing partially behind the screen during the lowering event. The screen was then removed to reveal either one object (inconsistent outcome for adults) or two (consistent outcome for adults). The single object in the inconsistent outcome was always that object which had been lowered into place first; it was also on same side as the object in the single object baseline trials.

There were four alternating orders of test trials, one-two-two-one-one-two, one-two-two-one-two-one, two-one-one-two-one-two, and two-one-one-two-two-one. Order of outcomes (consistent first, inconsistent first) and the side on which the single object appeared in the single object displays were counterbalanced across infants.

2.1.4.2. Flexible object condition The flexible object condition was identical to the rigid object condition in all respects, except for differences that derived from the different stimulus. During the tactile exposure phase, the object was initially displayed to the infant folded into a rectangle in the experimenter's hand, as she approached the high chair. Then it was dangled in a straight line and lowered onto the high chair into a pyramid shape, and the infant was encouraged to manipulate it for a total of 30 s.

The baseline and test trials were identical to those of the rigid object condition. During each baseline and test event, the flexible object was first displayed folded in the experimenter's hand, dangled in a straight line (partially hidden behind the screen during lowering events behind the screen), and then placed into a pyramid shape on the stage floor.

2.1.4.3. Sand condition Each infant in the sand condition was given a chance to handle some sand during the tactile exposure phase. The experimenter stood away from the infant and held a transparent plastic measuring cup containing sand in one hand and an empty measuring cup in the other. He drew the infant's attention to the sand by pouring it back and forth between the containers. Then he approached the infant's high chair and poured the sand onto the high chair tray into a pile. Infants often reached for the pile of sand immediately. If they did not, the parent prompted the infant to manipulate the sand. Each infant handled the sand for 30 s.

The baseline and test trials exactly paralleled those of the rigid and flexible object conditions. During each pouring event, the sand was initially presented in a transparent measuring cup, and then poured onto the stage floor into a pyramid-shaped pile. In cases of pouring behind the screen, the stream of sand was partially visible above the screen for the same amount of time as the rigid object was dangled there and as the flexible object was partially visible in its straight line configuration.

Each lowering event was timed as follows: object or sand introduced (2 s), poured or lowered to mid-way in trajectory toward floor, dangled in position (5 s), lowered to stage floor (1 s). On test trials, the first entity on the stage floor was left visible for 2 s before being covered by the screen.

In all of the studies reported in this paper, looking times were measured after the baseline or test event was completed, and trials ended when the infant looked away from the display for 2 s continuously having looked for at least 0.5 s before that. Inter-observer agreement was assessed by calculating the looking time measurements of both observers for each trial, and then the mean proportion of agreement per trial. Primary observer data were collected for all of the infants, but secondary observer data were collected for only 25 of the 46 infants. The remaining 21 infants were not doubly observed due to corruption of the original videotapes. The mean inter-observer agreement for the doubly observed data was 0.92.

2.2. Results

Whenever means are reported below, their associated standard deviations will be noted in parentheses: M (SD). Unless otherwise indicated, post-hoc analyses are Fisher's protected LSD tests, and alpha has been set at 0.05. Omnibus ANOVAs found no significant effects of sex, side of presentation, or order of trials, and therefore the following analyses collapse across these variables.

Infants' looking times during the four baseline and six test trials were averaged into two paired groupings for each participant, average looking times at one entity and average looking times at two entities during both baseline and test trials. A $2 \times 2 \times 3$ ANOVA examined the effects on looking times of the within participants variables of outcome number (one, two), and trial type (baseline, test), and the between participants variable of stimulus type (rigid object, flexible object, sand). The mean looking times for each condition are in Table 1 (see Fig. 1 for a graph of the summary data). There was a marginal main effect of number ($F(1,43) = 3.4$, $P = 0.07$). Participants may have preferred looking at two entities, 4.8 s (2.6), over looking at one entity, 4.4 s (2.3). There was a significant main effect of trial type ($F(1,43) = 4.4$, $P < 0.05$). Infants looked longer during the baseline trials, 5.0 s (2.7), than during the test trials, 4.2 s (2.1). However, there was no main effect of stimulus ($F(1,43) = 2.2$, NS).

"Success" on this task consists of longer looking at the inconsistent outcome of one object/pile during the test trials, relative to whatever baseline preference the infant may have had for one outcome or the other. Fig. 1 presents the difference of difference scores in

Table 1
Mean looking time in seconds for Experiments 1 and 2, with standard deviations in parentheses

	Familiarization		Test	
	One	Two	One	Two
Experiment 1				
Rigid object	3.6 (1.6)	5.0 (3.1)	4.8 (2.1)	3.6 (1.5)
Flexible object	5.8 (2.9)	5.9 (3.8)	4.3 (2.2)	5.5 (2.8)
Sand	4.8 (2.5)	5.1 (2.2)	3.3 (1.8)	3.9 (1.3)
Experiment 2				
Rigid object	6.2 (3.1)	8.0 (4.4)	5.7 (3.7)	4.7 (2.8)
Flexible object	4.5 (2.6)	6.4 (3.8)	6.0 (3.1)	4.8 (3.3)
Sand	6.9 (4.5)	4.7 (1.7)	3.6 (1.5)	3.6 (1.9)

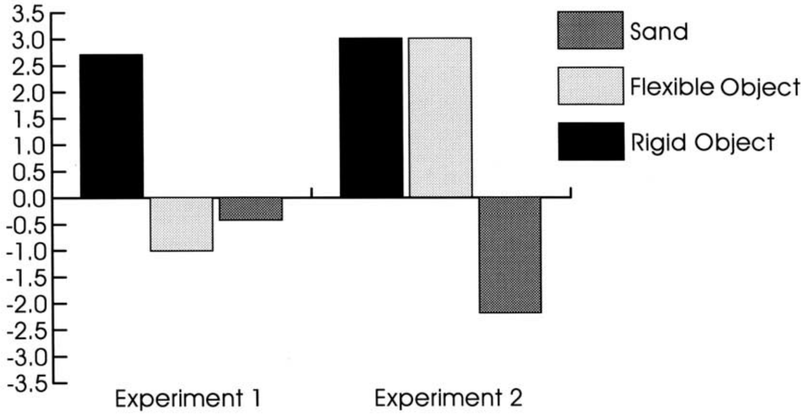

Fig. 1. Mean difference of difference scores for each condition for both experiments. Those scores are the degree or preference for one object/pile in test trials minus the degree of preference for one object/pile during baseline trials.

looking times: test trials (1 entity outcomes − 2 entity outcomes) − baseline trials (1 entity outcomes − 2 entity outcomes). Success consists of a positive value and a significant Outcome number (one, two) × Trial type (baseline, test) interaction, with a greater preference for one object/pile outcomes during the test trials than during the baseline trials. The overall interaction of Outcome number × Trial type was not significant ($F(1, 43) = 0.637$, NS). However, the three-way interaction of Outcome number × Trial type × Stimulus was statistically significant ($F(2, 43) = 4.4$, $P < 0.02$). There were no other significant main effects or interactions.

We sought to establish the source of the three-way interaction, and to determine whether infants succeeded with any of the three stimulus types. Therefore, we carried out separate 2 × 2 ANOVAs examining the effect of outcome number (one, two) and trial type (baseline, test) for each stimulus type: rigid object, flexible object, sand. In the rigid object condition, there were no main effects of number or trial type, but there was a significant Outcome number × Trial type interaction ($F(1, 15) = 10.0$, $P < 0.01$). Infants in this condition showed an increased preference for the one-object outcome during the test trials compared with the preceding baseline trials (Fig. 1).

In contrast to the rigid object condition, there were no Outcome number × Trial type interactions in either the flexible object condition ($F(1, 13) = 0.50$, NS), or the sand condition ($F(1, 15) = 0.77$, NS). There was a significant main effect of trial type for the sand condition ($F(1, 15) = 5.7$, $P < 0.05$), and infants looked longer during baseline trials, 5.0 s (2.3), than during test trials, 3.6 s (1.5). There were no other significant main effects in these two analyses.

Thus, the significant three-way interaction in the overall ANOVA was due to success in the rigid object condition, in the face of failure in both the flexible object and sand conditions. To further establish that the pattern of results was different in the rigid object condition from that in each of the other two conditions, and that the sand and flexible object conditions did not differ from each other, three additional 2 × 2 × 2 ANOVAs were carried out comparing each condition with the others in pairs: rigid object vs. sand, rigid object vs. flexible object, and flexible object vs. sand. We were particularly interested in the three-way interaction results, as they will reflect success in the rigid object condition contrasted with failures in the flexible object and sand conditions. The three-way interaction results are presented in Table 2. Three-way interactions of stimulus type, trial type and outcome number were significant in both the rigid object/sand analysis and in the rigid object/flexible object analysis, but not in the flexible object/sand analysis.

A second reflection of success in this task is outright preference for the inconsistent outcome of one object during the test trials. Given that the 2×2 interaction results varied by stimulus type, we began by examining whether stimulus type influenced the looking times during the test trials alone. A one-way ANOVA examined the effect of stimulus type on test trial difference scores (one object/pile looking times − two objects/piles looking times). There was a main effect of stimulus type ($F(2,43) = 4.1$, $P < 0.03$). This main effect was due to the fact that infants looked longer at one object/pile than at two during the test trials for the rigid object condition (difference score: 1.2 s (2.6)), but not during the flexible object condition (difference score: −1.2 s (3.3)) or the sand condition (difference score: −0.65 s (1.0)). Three Fisher protected LSD post-hoc tests confirmed that the rigid object preference for one in the test trials was longer than that for the flexible object condition ($P < 0.01$), and that for the sand condition ($P < 0.02$), whereas the latter two conditions did not differ (NS).

Next, although outright preference for one object on the test trials is not necessary to demonstrate a sensitivity to the inconsistent outcome (given baseline preferences for two objects), we carried out Fisher protected LSD tests on the looking times in the test trials within each condition. In the rigid object condition, infants looked reliably longer at one-object outcomes ($P < 0.02$). The two outcomes were not differentiated from each other in either of the other two conditions (flexible object: $P < 0.26$; sand: $P < 0.20$).

Finally, the overall findings were reflected in the patterns of looking preferences of individual infants. We computed a difference of difference scores for each infant: the degree of preference for looking at one object during the test trials minus the degree of preference for looking at one object during baseline trials (the combined difference data are shown in Fig. 1). In the rigid object condition, 14 of 16 participants looked relatively longer at the outcome of one object during test trials than during the baseline trials (Wilcoxon $Z = 2.7$, $P < 0.01$), whereas in the flexible object condition only eight out of 14 did so (Wilcoxon $Z = 1.1$, NS). In the sand condition only six out of 16 participants looked relatively longer at one pile during tests (Wilcoxon $Z = 1.11$, NS).

Table 2
Three-way interaction results from $2 \times 2 \times 2$ ANOVAs: Outcome number (one, two) × Trial type (familiarization, test) × Stimulus type, for the three possible pairs of stimulus type comparisons

Stimulus pair	Experiment 1	Experiment 2
Rigid object vs. sand	$F(1,30) = 10.35$, $P < 0.005$	$F(1,29) = 6.7$, $P < 0.02$
Flexible object vs. sand	$F(1,28) = 0.195$, NS	$F(1,29) = 9.3$, $P < 0.005$
Rigid object vs. flexible object	$F(1,28) = 5.278$, $P < 0.05$	$F(1,30) = 0.09$, NS

2.3. Discussion

Infants in all three conditions received the same number of baseline exposures to one-entity outcomes and to two-entity outcomes. There was a small non-significant overall preference for two objects in the baseline trials that did not differ across conditions. Furthermore, infants in the three conditions found the three types of entities comparably interesting during baseline trials (see Table 1).[3] Nevertheless the pattern of looking on the test trials differed across the three conditions. The infants in the rigid object condition had an outright preference for the inconsistent outcomes during the test trials whereas those in the other conditions did not. The preference for the inconsistent one-outcome entity in the rigid object condition differed significantly from the degree of preference for this outcome in the other two conditions, which did not differ from each other.

Each test trial in each condition began with one entity being lowered onto the stage floor and being left there in full view for 2 s before being covered by the screen. With respect to perceptual properties of the entities resting on the stage floor, the entities were identical (sand, rigid object) or nearly so (flexible object relative to the other two). The entity seen on the stage floor before the screen was raised was exactly the same as that revealed in the one-entity (inconsistent outcome) trials. Thus, the low level within-trial familiarity hypothesis of Cohen and Marks (in press) predicts longer looking at one-entity outcomes equally in all three conditions. This prediction was not borne out; it was only in the rigid object condition that infants looked longer at the one-object outcomes than at the two-object outcomes.

We conclude that this experiment reflects infants' capacities to track individual entities through time and occlusion, updating representations of an array consisting of a single hidden entity as an additional one is inserted. In Experiment 1, non-rigidity appears sufficient to disrupt successful tracking; there is no evidence from Experiment 1 that non-cohesion contributes any additional difficulty. Infants failed both with the non-rigid, cohesive object and with the non-rigid, non-cohesive sand.

We see two distinct possible interpretations of the finding that non-rigidity interferes with entity tracking under these conditions. First, the models of the hidden objects may be imagistic, requiring that the infant create an image of what the entity will look like on the stage floor. The child may anticipate what the resulting array will look like, comparing the revealed array with the represented array on the basis of appearance. Non-rigidity may burden this process; it may be difficult for the child to predict what shape the sand or flexible object will end up in, given that each assumes three different configurations during the lowering events. On this interpretation, success in the rigid object condition is due to the fact that the rigid object maintains a constant shape throughout the events, facilitating the prediction of the shape of the entity behind the screen, and thus facilitating an imagistic representation of the objects there (shape prediction interpretation). Notice that the shape prediction interpretation differs from the low level within-trial familiarity hypothesis. It posits that the final array is representated in terms of individuated, permanent objects. See Feigenson, Carey, and Hauser (2002) for evidence that perceptual features are bound to object files and representations of arrays are compared on the basis of such features.

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[3] There is no main effect of stimulus type for the baseline trials data ($F(2, 43) = 1.6$, NS).

Second, and related, perhaps the single screen design left ambiguity as to whether the sand was being poured into two separate piles or one large pile, and whether the flexible object was being lowered into two separate pyramids or one large one (location ambiguity interpretation). This solid object condition would not be subject to this ambiguity, because two rigid pile-shaped objects could not merge into a single large pile-shaped object.

Experiment 2 was designed to explore these alternative interpretations of the failures in the sand and flexible object conditions. Experiment 2 is identical to Experiment 1 except that the entities are hidden behind two separate small screens rather than behind one large screen. If the shape prediction interpretation is right, then the results of Experiment 2 should be the same as those of Experiment 1, since the change to two separate screens makes it no easier to predict the final pile/pyramid shape resting on the stage floor of the sand/flexible object. If the location ambiguity interpretation of the failure in the sand and flexible object conditions of Experiment 1 is true, then infants should succeed in all three conditions of Experiment 2, for there is no location ambiguity in Experiment 2. The two piles/flexible objects cannot merge into one, because they are behind separate screens. Finally, Experiment 2 allows us to further explore whether non-cohesion adds further difficulty to individual tracking, beyond that of non-rigidity. If non-cohesion prevents the establishment of representations of individual piles of sand, then infants should fail in the sand condition, even when each pile is hidden behind a separate screen. Such an outcome would suggest that the failures in Experiment 1 in the sand and in the flexible object conditions were due to at least partly distinct causes.

3. Experiment 2

3.1. Method

3.1.1. Participants

Forty-seven healthy, full-term infants participated in Experiment 2, 24 boys and 23 girls. Their mean age was 8 months and 0 days (SD 9 days). Eight additional infants were excluded due to fussiness, experimenter error or equipment failure. One additional infant was excluded from the data analysis because of relatively long baseline looking times (>3 SD longer than group means). Each infant was randomly assigned to one of three stimulus groups: rigid object, $n = 16$; flexible object, $n = 16$; or sand, $n = 15$. Participants were recruited and compensated as in Experiment 1.

3.1.2. Procedure

The setup and stimuli were identical to that of Experiment 1, and the procedure was similar in terms of overall structure. There was a tactile exposure section, followed by four baseline trials, followed in turn by a series of six test trials, alternating between consistent and inconsistent outcomes. However, unlike Experiment 1, the stimuli were hidden behind two side by side 35×35 cm screens instead of a single screen. These screens were both colored orange and they contrasted with the dark blue of the display floor and the black backdrop. When placed on the display floor, a distance of 16 cm separated the two screens.

The screens were introduced and withdrawn by the experimenter through the top of the display area.

Infants were first introduced to the screens after the tactile exposure section and before the baseline trials. The participant was first shown an empty display, and then the two screens were lowered into place side by side on the display floor. The experimenter drew the infant's attention to the screens by calling out to the infant as the screens were lowered. The screens were left in place for 30 s and then removed for the baseline trials to begin.

The tactile exposure phase of the experiment was identical to that of Experiment 1. After the infants were introduced to the screens, as described above, the baseline trials unfolded as in Experiment 1. Infants in each stimulus condition received two pairs of baseline trials, two in full view and two behind the screens. Those in full view were identical to those of Experiment 1. The screened pair began with an empty stage, and then the two screens were lowered onto the stage. On one-entity screen baseline trials, one of the entities (rigid object, flexible object, portion of sand) was lowered/poured behind one of the screens. The screens were then removed, revealing the object/a pile of sand resting on the stage floor. On two-entity screen baseline trials, two of the entities were simultaneously lowered/poured, as in Experiment 1, except in this case each behind a separate screen. The screens were then removed, revealing the two objects/two piles of sand on the stage floor. Counterbalancing was as in Experiment 1.

The test trials unfolded as in Experiment 1. First, one entity (rigid object, flexible object, or portion of sand) was lowered or poured, in full view, onto the stage floor. Next, both screens were introduced, and one hid the entity resting on the floor. Then the second entity was lowered/poured behind the other screen, after which the screens were removed, revealing the consistent outcome of two entities or the inconsistent outcome of one entity in alternating test trials. Counterbalancing was as in Experiment 1. Primary observer data were collected for all of the infants, and secondary observer data were collected for 12 of the 48 infants. The remaining 36 infants were not doubly observed due to corruption of the original videotapes. The mean inter-observer agreement for the doubly observed data was 0.90.

3.2. Results

An omnibus ANOVA found no effects of sex, side of presentation, or order of trials; subsequent analyses collapse across these variables. As in Experiment 1, we began with a $2 \times 2 \times 3$ ANOVA examining the effects of outcome number (one, two), trial type (baseline, test) and stimulus type (rigid object, flexible object, sand) on looking times. See Table 1 for the mean looking times for each condition. There was no main effect of number ($F(1,44) = 0.05$, NS), nor of stimulus ($F(2,44) = 1.5$, NS). However, there was a main effect of trial type ($F(1,44) = 10.8$, $P < 0.005$). As in Experiment 1, participants looked longer during baseline trials, 6.1 s (3.7), than during test trials, 4.8 s (3.2). There was a three-way interaction of Outcome number × Trial type × Stimulus ($F(2,44) = 5.3$, $P < 0.01$). There were no other significant main effects or interactions.

To elucidate the interaction and to probe the effects of stimulus differences, three follow-up 2×2 ANOVAs were carried out, examining the effects of outcome number and trial type on looking times in each of the three stimulus conditions. The pattern of success is an Outcome number × Trial type interaction, such that infants look relatively longer at the one-object outcomes during the test trials than they did in the baseline trials. Table 1 contains the mean looking times for each condition and Fig. 1 presents the difference of difference scores in each condition.

The rigid object 2 × 2 ANOVA of Experiment 2 revealed a main effect of trial type ($F(1,15) = 6.2$, $P < 0.05$). Infants looked longer during the baseline trials, 7.1 s (3.9), than during the test trials, 5.2 s (3.3). There was a marginally significant Outcome number × Trial type interaction ($F(1,15) = 4.2$, $P = 0.06$). Infants had a baseline preference for two-object outcomes and they reversed this preference during the test trials. There were no other significant effects. Thus, the infants succeeded in the rigid object condition, just as they did in Experiment 1.[4]

The 2 × 2 ANOVA examining the effects of outcome number and trial type on looking times in the sand condition yielded a main effect of trial type ($F(1,14) = 11.6$, $P < 0.005$). Infants looked longer during baseline trials, 5.8 s (3.5), than during test trials, 3.6 s (1.7). There was no significant Outcome number × Trial type interaction ($F(1,14) = 2.6$, NS). As in Experiment 1, the infants failed in the sand condition of Experiment 2.

However, in contrast to Experiment 1, in which infants in the flexible object condition failed, infants succeeded in the flexible object condition of Experiment 2. The 2 × 2 ANOVA revealed no main effects of trial type or outcome number, but there was a significant Outcome number × Trial type interaction ($F(1,15) = 8.3$, $P < 0.02$). Infants differentiated the outcomes in the test trials, looking longer at the inconsistent one-object outcome, relative to their baseline preference (see Fig. 1).

Thus, in Experiment 2, we see success in the rigid and flexible object conditions and failure in the sand condition. To further confirm whether the rigid and flexible object conditions patterned together and that each patterned differently from the sand condition, we conducted three additional 2 × 2 × 2 ANOVAs, analyzing the conditions in pairs. The three-way interaction results of these analyses are presented in Table 2. There was no three-way interaction in the rigid object/flexible object analysis. However, both the rigid

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[4] Three additional ANOVAs examined the effects of experiment, trial type and outcome number on looking times for each stimulus type separately. In the rigid object condition, there was an effect of experiment ($F(1,30) = 5.9$, $P < 0.05$). Infants looked longer during Experiment 2 than during Experiment 1, 6.1 s (3.7) and 4.2 s (2.2), respectively. There was also a main effect of trial type ($F(1,30) = 4.8$, $P < 0.05$). Infants looked longer during familiarization than during tests, 5.7 s (3.5) and 4.7 s (2.7), respectively. There was a significant Trial type × Outcome number interaction ($F(1,30) = 11.6$, $P < 0.002$). Most importantly, there was no three-way interaction of Outcome number × Trial type × Experiment ($F(1,30) = 0.08$, NS). The significant implication of the latter result is that in the rigid object conditions, infants in both experiments differentiated the test trials from their baseline preferences to the same extent. In the sand condition, there were no effects of experiment or number, but there was a main effect of trial type ($F(1,29) = 17.2$, $P < 0.0005$). There was also a significant Experiment × Outcome number interaction ($F(1,30) = 5.8$, $P < 0.05$). Finally, and most importantly, there was no three-way interaction of Trial type × Outcome number × Experiment. Sand condition infants in both experiments failed to differentiate the test trial outcomes from the baseline trial outcomes to the same extent. In the flexible object condition, the three-way interaction was significant ($F(1,28) = 5.3$, $P < 0.05$). Infants looked longer at the one-object test outcomes, relative to baseline, during the test trials of Experiment 2, but not of Experiment 1. There were no other significant main effects or interactions in any of these analyses.

object/sand ANOVA and the flexible object/sand ANOVA revealed significant three-way interactions of Outcome number × Trial type × Stimulus.

We then turned to the question of success as reflected in the outright preference for the inconsistent outcome in the test trials. As in Experiment 1, infants in every condition saw similar baseline displays. We sought to determine whether a preference for the outcome of a single object in test trials varied as a function of the stimulus type. To assess this, we computed difference scores for the test trial looking times alone for each participant and analyzed them by means of a one-way ANOVA. There was no main effect of stimulus, although the differences between looking at one and looking at two during the test trials were consistent with the previous analyses; they were 0.99 s (2.0), 1.1 s (1.4) and −0.176 s (1.6) for the rigid object, flexible object, and the sand conditions, respectively. Planned post-hoc analyses confirmed that the rigid object and flexible object conditions did not themselves differ, and neither did the rigid object and sand conditions, although the flexible object and the sand conditions were different ($P < 0.05$).

Outright preference for one entity in the test trials is not necessary to demonstrate success. Nonetheless, we carried out post-hoc analyses on the test trial looking times for each of the three stimulus conditions. None of the post-hoc analyses of the test trial data alone were significant. Although infants in both object conditions looked longer at the inconsistent outcomes than at the consistent ones (see Table 1), these differences by themselves were not significant. Success in Experiment 2 was relative to baseline preferences. As Cohen and Marks (in press) demonstrate, the degree of preference for two-entity outcomes over one-entity outcomes increases over time during experiments such as these; outright preference for the inconsistent one-object outcomes must counteract this baseline preference.

An analysis of the individual participants' data supports the general pattern of findings reported above. We compared the degree of looking at one object during test trials with the degree of looking at one object during baseline trials for each participant (see the difference scores in Fig. 1). In the rigid object condition, 12 out of 16 participants had a stronger looking time preference for one object in test trials than in baseline trials (Wilcoxon $Z = 2.0$, $P < 0.05$). Similarly in the flexible object condition, 12 out of 16 participants had a stronger looking time preference for one object in test trials than in baseline trials (Wilcoxon $Z = 2.4$, $P < 0.02$). However, in the sand condition there was no general tendency for a stronger looking time preference for one object on the test trials, relative to the baseline trials. Only six out of 15 participants showed this pattern (Wilcoxon $Z = -1.4$, NS).

In summary, as Fig. 1 indicates, infants succeeded in the rigid object conditions of both experiments, and failed in the sand conditions of both experiments. Infants in the flexible object conditions failed in single screen Experiment 1 but succeeded in the two screen version of Experiment 2.

3.3. Discussion

In two of the three stimulus conditions, the results of Experiment 2 were just as in Experiment 1. Infants in the rigid object condition looked longer at the inconsistent outcome relative to baseline, whereas infants in the sand condition did not. The results in the third stimulus condition, the flexible object condition, differed across the two experiments: failure in Experiment 1, success in Experiment 2.

The results of Experiment 2 are not consistent with the shape prediction hypothesis concerning the failures in the sand and flexible object conditions of Experiment 1. If these failures were due entirely to the inability to predict what the lowered/poured entity would look like on the stage floor, infants should also have failed in both non-rigid conditions in Experiment 2. They did not; they succeeded in the flexible object condition of Experiment 2. Nor are the failures in the sand and flexible object conditions of Experiment 1 fully explained by the location ambiguity hypothesis. If the failure were due to ambiguity concerning the location of pouring/lowering, allowing the possibility of single (large) entity outcomes in these conditions of Experiment 1, then the infants in all three conditions of Experiment 2 should have succeeded. The two screen condition of Experiment 2 removed all ambiguity concerning where the entities were being lowered/poured, but infants still failed in the sand condition. However, the results of Experiment 2 leave open the possibility that the location ambiguity hypothesis accounts for the failure in the flexible object condition of Experiment 1, for when the ambiguity about location was removed in Experiment 2, infants in the flexible object condition succeeded. Eight-month-old infants are able to establish representations of non-rigid objects and track them through time.

Apparently, tracking portions of sand from container through pouring to piles poses a problem for infants beyond those created by non-rigidity and shape malleability. Non-cohesion itself may be the relevant factor. Non-cohesion interferes with tracing numerical identity of individuals, and in the present experiments, like those of Chiang and Wynn, infants fail to individuate and trace identity of non-cohesive entities, under conditions in which they succeed with cohesive ones.

4. General discussion

The data from these experiments, like those of Chiang and Wynn (2000), are not consistent with low level perceptual novelty/familiarity interpretations, such as the Cohen and Marks (in press) within-trial familiarity preference hypothesis. In all of the test trials in these experiments, infants first saw the single entity on the stage floor, before it was covered by a screen, the identical outcome that would be the one-entity outcome in the inconsistent outcome trials. Thus, if longer looking at the inconsistent outcome was due to a within-trial familiarity preference, infants should have consistently succeeded in all of the conditions of both series of studies. Yet they did not. They succeeded when the entity was a rigid object, both in Chiang and Wynn's study and in Experiments 1 and 2 of the present studies. They failed robustly when the entity was non-cohesive (either because it was decomposed into separate objects and then recombined or because it was sand), and they were also affected by whether the entity was rigid or not (Experiment 1 of the present studies). Experiments 1 and 2, taken together with those of Chiang and Wynn, support the conclusion that 8-month-old infants are forming models of the hidden objects, updating them when new individuals are inserted into the arrays, and that the processes that individuate and track individuals through time are sensitive to material kind.

The infants in the present experiments were older than the 4-month-old infants of Cohen and Marks. It is possible that the low level within-trial familiarity hypothesis is true for younger infants, and that it is not until infants are older that they are actually creating models of sets of hidden objects behind these screens (see Carey, in press, for a critical discussion). The present data bear against the low level familiarity hypothesis only for 8-month-olds.

Eight-month-old infants succeeded in the rigid object conditions of both experiments, replicating previous studies that found that 8-month-old infants look longer at the inconsistent outcome in $1 + 1 = 2$ or 1 events (Chiang & Wynn, 2000; Uller et al., 1999). Thus, it appears that by 8 months of age, at least, infants create representations of an object hidden behind a screen. Since the second object, introduced from above, appears to be identical to the hidden one, infants must have drawn upon spatio-temporal discontinuity to represent a second object, thereby creating a model of two objects behind the single screen (Experiment 1) or each of the two screens (Experiment 2; Chiang & Wynn, 2000). By 8 months of age, infants build representations of rigid, cohesive individuals and track them through time and occlusion.

The important result from the present studies is that infants of this age *failed* to build representations of non-cohesive individuals (sand) and track them through time, under conditions in which they succeed with cohesive individuals. These data support the Chiang and Wynn (2000) assumption that it was non-cohesion, per se, that interfered with object tracking in their studies. The failure in the sand condition of Experiment 2 is particularly striking, for it is a failure of sand permanence. To succeed, the child need only represent "sand behind that screen, sand behind that screen", yet when the screens were removed, revealing sand behind only one of the screens, infants showed no increased looking at the display. Infants failed to represent portions of sand as something behind the screen, just as they failed to represent piles of blocks as something behind the screen in the studies of Chiang and Wynn. They failed to form a representation of a portion of sand as a particular individual that is traced through space and time, just as the infants in Chiang and Wynn's experiments failed to represent a pile of blocks as a particular individual that is traced through space and time.[5]

Research on *object permanence* in infancy, and on *object files*, *object tracking* in adults (if the identification of the two literatures is correct) is well named. Bounded, cohesive objects, including flexible, non-rigid ones, have a privileged status in the computational system that establishes representations of individuals and tracks them through time. This is not a mystery. If an entity breaks into many parts, there is no answer to the question of which part is the same one as the original. Of course, adults are extremely flexible in the individuals they can represent – collections of individual objects may be construed as

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[5] Of course, "object permanence" is intimately linked to computations of individuation and numerical identity. We do not credit the child with representations of object permanence unless the child represents the revealed object as the "same one" (numerical identity) as that seen hidden. In these studies with rigid objects, infants clearly represent the second object as numerically distinct from the first, for they update their model of the single hidden object to include the second when it is introduced. They are sensitive to numerical identity/non-identity of rigid objects. Infants failed to demonstrate sand permanence in these studies, and failed to demonstrate flexible object permanence in Experiment 1, just as they failed to demonstrate "collection" permanence in Chiang and Wynn (2000).

individuals (a stack, a herd, an army), and individual portions of non-cohesive materials (a pile of sand, a cup of sand) are also represented. Apparently, 8-month-old infants have not yet begun to flexibly construct concepts like "pile" or "portion" that would allow them to track piles of blocks and sand through time.

Adults, when looking at a pile of sand, may encode it as "sand" or as "pile", i.e. as an individuated entity (pile) or as a non-individuated entity (sand). Other experiments indicate that infants of this age can form non-quantitative representations of sand. They look longer if sand poured into a closed container comes out the other end than if it does not, reversing the pattern of looking if the sand is poured into an open cylinder (Baillargeon, 1995), and they look longer if sand poured onto a shelf is revealed under the shelf rather than on top of it (Huntley-Fenner, Carey, & Klatt, 2002). Apparently, under the present conditions, infants encode these entities as *sand* or *stuff*. These experiments provide the first tentative evidence that infants make a principled, quantificational distinction between cohesive and non-cohesive entities that goes beyond the problems of perceptually encoding non-rigidity. Just as all languages with count/mass distinctions treat non-solid substances as non-individuated entities, so perhaps does the pre-linguistic representational system of human infants.

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