British Journal of Developmental Psychology (1995), 13, 113–142 *Printed in Great Britain*

Spatiotemporal continuity, smoothness of motion and object identity in infancy

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A preferential looking method served to investigate 4-month-old infants' apprehension of the identity of objects over successive encounters. In Expts 1 and 2, infants were familiarized with events in which objects moved either continuously or discontinuously behind two narrow screens. Subsequent looking times to one- vs. two-object displays provided evidence that infants apprehend object identity in accord with the principle that objects move continuously. In Expts 3 and 4, infants were familiarized with events in which objects moved behind one wide screen with an occlusion time either appropriate or inappropriate to their visible speed. Subsequent looking times to one- vs. two-object displays provided no evidence that infants apprehend object identity in accord with the principle that objects move smoothly. The findings are contrasted with those of studies of infants' search for objects. Continuity may be an early-developing, core principle by which humans individuate objects, but this principle may not guide all early-developing actions on objects.

Human adults experience physical objects as entities that persist over time, even though perceptual encounters with objects are usually brief and intermittent. Although the capacities that underlie this experience appear to be quite complex (see Geach, 1962; Hirsch, 1982; Hume, 1962; Wiggins, 1980), one principle that seems to be central to adults' apprehension of identity is the *principle of continuity*: an object traces exactly one connected path over space and time (Hirsch, 1982).

The principle of continuity can guide adults' apprehension of identity, because it encompasses two symmetrical constraints on object motion (Fig. 1). According to the continuity constraint, the spatiotemporal path of one object can contain no gaps: two object appearances that are seen to be separated by a gap therefore must be appearances of two distinct objects. According to the solidity constraint, the spatiotemporal paths of

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distinct objects cannot intersect such that the objects occupy the same place at the same time: two object appearances that are seen to be connected by a single, continuous path of motion therefore must be appearances of a single object.

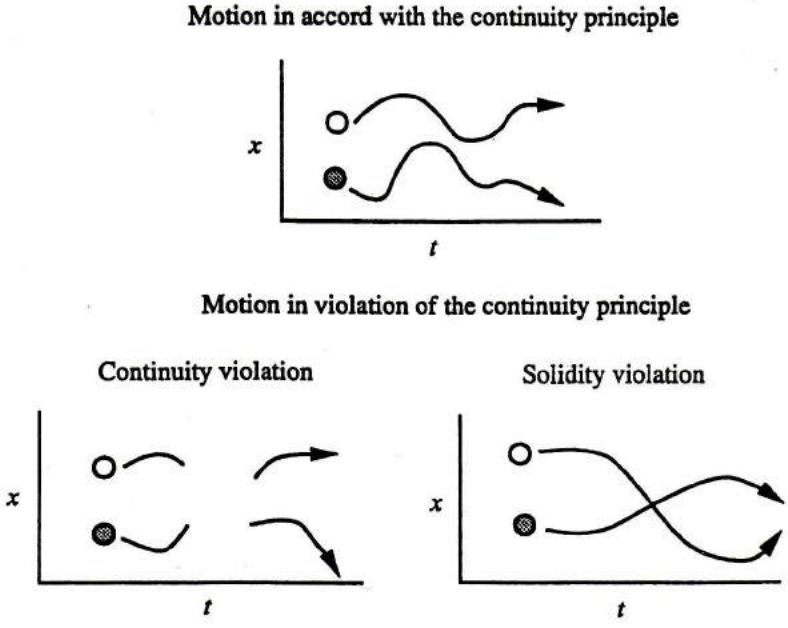

Figure 1. The continuity principle. Arrows indicate the path of motion of an object over space (depicted one-dimensionally on the vertical axis) and time (horizontal axis).

A second principle that exerts some influence on adults' apprehension of object identity is the principle that objects move smoothly. The smoothness principle is related to the principle of inertia in classical mechanics, whereby objects undergo linear motion at a constant speed in the absence of forces, and it appears to influence adults' perception of the persistence of objects under circumstances that are otherwise ambiguous. We refer here to the smoothness principle rather than the inertia principle, because the tendency to extrapolate smooth object motion may extend to curvilinear motions as well as linear motions, contrary to inertia (McCloskey, 1983; von Hofsten, 1983). When an object moves smoothly behind a wide occluder and returns to view at the same visible speed, for example, adults are more apt to perceive a single, persisting object if the duration of occlusion is appropriate to the speed of the object's motion (Michotte, 1963). Because forces are omnipresent and often go unnoticed, however, the smoothness principle does not provide a reliable basis for apprehending the identity of a moving object over successive encounters: events presenting a change in object motion need not present a change in object identity. For this reason, the smoothness principle appears to exert only a minor influence on adults' apprehension of object identity, and it is readily overpowered by the principle of continuity. Presented with an event in which object motion is continuous (that is, contains no gaps) but not smooth, adults perceive a single object that changes its motion, not a series of distinct objects that exist successively.

The present research focuses on the early development of the ability to apprehend object identity in accord with these two principles. We compare infants' sensitivity to the

continuity principle and the smoothness principle, in order to shed light on a discrepancy between two accounts of infants' developing conceptions of physical objects, each based on a different set of methods.

Object identity, object search and preferential looking at novel events

Infants' apprehension of object identity has been investigated primarily through studies of infants' visual and manual search for hidden objects. Infants make no attempt to look or reach for a hidden object until about 5 and 8 months of age, respectively, and their subsequent search for objects is inappropriate in a number of respects (Harris, 1975, 1987; Piaget, 1954). Early visual and manual search are most successful if an object moves on a smooth path and reappears at a predictable location. In contrast, infants' search often fails dramatically if an object changes speed or moves to a new location, even if the object could be located by tracing its continuous path (e.g. Bower, Broughton & Moore, 1971; Piaget, 1954).

Detailed studies of visual search for objects provide further evidence that young infants' search is first guided by the principle that objects move smoothly but not by the principle that objects move continuously. Moore, Borton & Darby (1978) presented 5- and 9-month-old infants with an event in which an object moved at a constant speed, disappeared behind one side of a wide screen, and reappeared at the opposite side of the screen. After repeated presentations of this event, infants began to track the object's motion smoothly. Then infants in different conditions were presented with events in which the object either ceased to move smoothly (it was occluded for an inappropriately brief duration) or it ceased to move continuously (the wide screen was replaced by two narrow, spatially separated screens, and the object failed to appear between the screens). Visual tracking of these events was compared to tracking of otherwise comparable events that preserved the smoothness and continuity of object motion. Whereas infants at both ages showed disruptions of tracking when presented with the smoothness violation, only the older infants showed disruptions of tracking when presented with the continuity violation. Visual search appears to accord with the smoothness principle before it accords with the continuity principle.

Most observers have concluded that infants' changing search patterns reflect their changing conceptions of objects. According to Piaget (1954), infants initially have no conception of objects as entities distinct from their actions.[1] Conceptions of objects emerge over the first 18 months, as infants' actions become accommodated to objects and their motions. According to Bower (1982) and Moore & Meltzoff (1978), young infants do have conceptions that enable them to individuate objects, but their conceptions differ from those of older children and adults: a moving object is defined by its path and speed, and a stationary object is defined by its position. Although these

[1] Piaget's discussion of object permanence differs from more recent accounts in that he does not separate perception and cognition from action; thus the emphasis on search tasks. For example, in his discussion of manual search, he claims that the infant 'behaves as though the object were absorbed by the cloth and ceased to exist at the very moment that it left the perceptual field; or else, *and this amounts to the same thing*, he possesses no behavior enabling him to search for the object which has disappeared' (Piaget, 1973, p. 109, emphasis added). Here Piaget equates having a concept of an object to being able to act on that object. Because Piaget's discussion of object permanence is couched within his discussion of sensorimotor intelligence, he does not consider perception or cognition in the absence of action. Recent research does not refute Piaget's claims about infants' sensorimotor capabilities (for example, see Fischer & Bidell, 1991).

views differ in a number of respects (see Harris, 1987; Moore & Meltzoff, 1978), both agree that infants do not apprehend object identity in accord with the continuity principle.

If either of these interpretations were correct, conceptions of object identity would undergo radical developmental change. For adults, the particular actions performed on objects and the particular locations and motions of objects have little bearing on identity: a single body can be acted upon in different ways, it can occupy different places at different times, and it can undergo different motions. In contrast, an object must not move on a discontinuous path or coincide in space and time with a second object. The shift from a conception of objects centred on actions (e.g. Piaget, 1954) or on places and motions (e.g. Moore *et al.*, 1978) to a conception centred on continuity therefore would constitute a radical conceptual change (see Carey, 1991; Gopnik, 1988). The conceptual changes implied by the observations and interpretations of Piaget and his successors explain, in large part, the central place that studies of object search have played in discussions of early cognitive development.

Nevertheless, there are alternative interpretations of infants' search patterns that do not imply any radical differences between the conceptions of adults and infants. Perceivers of all ages may apprehend object identity in accord with the principle that objects move on connected, unobstructed paths. Object-directed search may fail to accord with this principle, because of limitations on infants' abilities to use knowledge of object identity to guide their coordinated actions.

Several considerations support the latter interpretation. First, visual search becomes adapted to the continuity of object motion by 9 months of age (Moore *et al*, 1978), whereas manual search does not accord consistently with the continuity principle until 18 months of age (Piaget, 1954). This age difference casts doubt on the view that a single conception underlies all developing forms of object search. Second, infants' manual search is affected by the length of an imposed delay between object hiding and search and by the number of potential places where an object could be found (e.g. Wellman, Cross & Bartsch, 1986). Although delay and choice often affect motor performance (Welford, 1968), neither seems to reflect conceptions of objects. Third, Piaget (1952) has presented a wealth of evidence that infants' earliest actions are relatively independent of one another, and that capacities for coordinated action develop gradually. The developing coordination among actions could account for many changes in object search. For example, Piaget reported that infants under 4 months tend to engage in single action patterns rhythmically and repeatedly and to continue the patterns despite changes in external conditions. Such a tendency may lead infants to look or reach for objects where they have looked or reached before. As a second example, Piaget reported that infants of 4–8 months cannot coordinate two distinct actions into a means–ends sequence. Such a limitation may prevent infants from searching for a hidden object by grasping and removing its occluder.

These considerations suggest that object search paradigms do not provide a complete picture of the early foundations of the apprehension of object identity. As a result, it is important to devise methods that assess the perception of object identity without relying on infants' search skills. Ideally, the methods should focus on a behavioural pattern that is present throughout the infancy period and undergoes little developmental change. Visual preference-for-novelty methods may meet this requirement.

If infants are presented with an event repeatedly, their looking time to the event tends to decline. When subsequently presented with new events, infants tend to look longer at the event they perceive as more novel (Tighe & Leaton, 1976). This preference is observed with infants as young as 1 day of age (Slater, Morison & Rose, 1984) and as old as 18 months (Ross, 1980). It is also observed with young children (Ross, 1980) and adults (e.g. Spelke, Breinlinger, Macomber & Jacobson, 1992). Preference for novelty methods have been used not only to investigate infants' sensory and perceptual capacities (e.g. Banks & Salapatek, 1983; Kellman, 1993), but also to explore infants' higher cognitive capacities (Baillargeon, 1993; Leslie, 1988; Spelke, 1991; Wynn, 1992). Some experiments in the latter category are the direct precursors to the present research and will be described in more detail.

In a number of experiments, Baillargeon (e.g. 1987; Baillargeon, Graber, DeVos & Black, 1990) presented infants with an object that disappeared behind a moving screen and then appeared to participate in events that adults would describe either as natural or as surprising, given the existence and location of the hidden object. For example, the hidden object might be retrieved by a hand from within an open cup (possible) or a closed cage (impossible). Infants under 6 months have looked longer at the events that adults describe as unnatural. These experiments provide evidence that infants represent the existence and location of a hidden object, and they suggest that infants are sensitive to complex constraints on objects' behaviour.

Further preferential looking experiments have explored the nature of the constraints on objects to which young infants are sensitive. Spelke *et al.* (1992) and Spelke, Katz, Purcell, Ehrlich & Breinlinger (1994) presented infants with events in which an object moved behind a screen and then was revealed at a position that was either consistent or inconsistent with constraints on object motion. Infants as young as 3 months looked longer at event outcomes that were inconsistent with the principle of continuity. In contrast, infants below 8 months showed no preference for event outcomes that were inconsistent with the principle of smoothness (Spelke *et al.*, 1994). Young infants appear to infer that hidden objects will move continuously but not that they will move smoothly.

The above studies and studies from other laboratories (e.g., Ball, 1973; Carey, Klatt & Schlaffer, 1992; Leslie, 1991; Wynn, 1992, Xu & Carey, 1992) suggest that infants' early conceptions of objects are not tied directly to their ability to act on objects; their search patterns may not reflect their underlying knowledge of objects. In addition, the studies suggest that early knowledge of physical objects encompasses the principle of continuity. Nevertheless, preferential looking experiments have not investigated directly how infants apprehend the identity of an object that moves out of view at one location and reappears at a different location. Such an approach would allow an assessment of infants' ability to use the principles of continuity and smoothness to apprehend object identity. The present experiments addressed this question.

Overview of the experiments

In each experiment, 4-month-old infants were presented repeatedly with an event in which an object moved in and out of view. When their looking time to the event had declined, the infants were given alternating presentations of test displays involving one

vs. two fully visible objects. Looking times to the test displays were compared to one another and to the looking times of infants in a control condition, who viewed the test displays without the prior familiarization sequence. If infants had perceived a single object moving throughout the familiarization event, they were expected to generalize habituation to the one-object test display and therefore to look less at that display than at the two-object display, relative to controls. If infants had perceived two objects in the original event, they were expected to show the reverse pattern of preferences: lower looking at the two-object test display than at the one-object test display, relative to controls.

Four experiments focused on occlusion events that have been used in studies of visual tracking. Experiments 1 and 2 investigated whether 4-month-old infants apprehend object identity in accord with the principle of continuity. Experiments 3 and 4 investigated whether infants apprehend object identity in accord with the principle of smoothness.

EXPERIMENT 1

Infants were presented with occlusion events devised by Moore *et al.* (1978), involving two spatially separated screens and one or two objects (Fig. 2). In the *continuous event*, an object started at one end of the display, moved smoothly behind the first screen, reappeared between the two screens, moved behind the second screen, and then reappeared and moved to the opposite end of the display. In the *discontinuous event*, no object appeared between the screens: an object moved from one end of the display to a position behind the first screen, a pause occurred, and then a second object appeared from behind the second screen and moved to the opposite end of the display. Adult subjects, asked to give their impressions of the number of objects in each of three events, reported that the continuous event involved one object and that the discontinuous event involved two objects (see Appendix).

In order to investigate infants' representations of the number of moving objects in each event, separate groups of infants were familiarized with the continuous event or with the discontinuous event. Then these two groups of infants, and a third group who received no familiarization sequence (the control condition), were presented with one-object and two-object test displays (Fig. 2), and their looking times were compared. If infants perceive the number of objects in these events in accord with the continuity principle, then the infants presented with continuous motion should perceive one object and those presented with discontinuous motion should perceive two objects. Infants' preference for the two-object display therefore should be highest in the continuous condition, intermediate in the control condition, and lowest in the discontinuous condition. If infants perceive the number of objects in these events only in accord with the smoothness principle, as suggested by studies of visual tracking (Moore *et al.*, 1978), then infants in both the continuous and the discontinuous conditions should perceive one object. Infants' preference for the two-object display should therefore be equally high in the continuous and discontinuous conditions and reliably lower in the control condition.

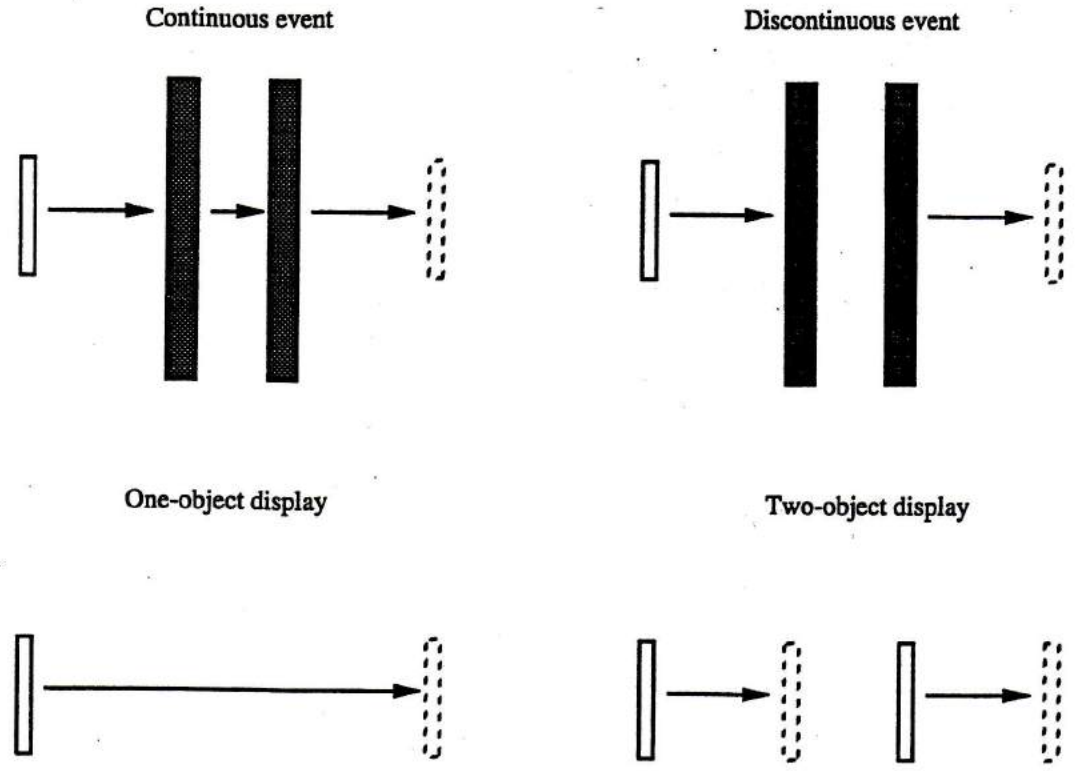

Figure 2. Displays for Expt 1. Arrows indicate the path of motion from an object's starting position (solid lines) to its final position (dotted lines) during one half-cycle of an event.

Method

Subjects

Participants were 24 full-term infants with no known or suspected abnormalities. The 13 female and 11 male infants ranged in age from 3 months 14 days to 4 months 30 days (mean age, 4 months 4 days). Two additional infants were eliminated from the sample because of fussiness (1) or experimenter error (1).

Display and apparatus

The events were presented within a three-sided, 122 cm × 188 cm × 48 cm white puppet stage. An infant sat in a semi-reclining seat facing the stage, 72 cm from the moving objects. A curtain in front of the stage could be opened or closed to reveal or conceal a display.

The occlusion events involved one or two cylinders that moved behind two vertical screens. The 19 cm long, 2 cm diameter cylinders (15.0° by 1.6° at the infant's point of observation) were painted yellow with red and blue dots in identical positions. They were suspended from behind by metal bars that could be moved horizontally through a slit in the back wall of the display. The two 53 cm high, 5 cm wide screens (43.0° by 4.3°) were painted grey. They stood on the floor of the stage 10 cm apart. In the continuous event, one cylinder began at the left side of the display and moved 61 cm to the right, disappearing and reappearing behind each screen in turn. At the end of its path, the cylinder reversed direction (with no perceptible pause) and moved leftward to the point of origin. In the discontinuous event, one cylinder began at the left, moved 23 cm to the right to a position centred behind the first screen, and then stopped. After a 2 s pause, a second cylinder, which was hidden behind the screen 15 cm further along the path of motion, moved into view and continued moving 23 cm to the right before reversing direction. Given the object's distance from the infant, an object was not visible when it was centred behind the screen, even if

the infant leaned to the left or right. In both events, the cylinder moved at the constant speed of 7.4 cm (5.9°)/s. Because the pause in the discontinuous event closely matched the duration required to traverse the distance between the mid-points of the screens in the continuous event, the continuous and discontinuous events were indistinguishable, except for the presence or absence of visible object motion between the screens.

The screens were removed for the test sequence. In the one-object event, one cylinder moved back and forth on a 61 cm path. In the two-object event, one cylinder moved 23 cm from the left to the position where the first screen had been, a 2 s pause occurred, and then the second cylinder, which had been standing in a stationary position 15 cm further along the path of motion, moved 23 cm further to the right before reversing direction. The cylinders again moved at the rate of 7.4 cm/s.

The motion of the cylinders was driven by motors controlled by a switch box behind the display. A tape-recording of motor noises was played throughout the experiment in order to mask the sounds that accompanied the objects' motions. Additional controls for motor noise are presented in Expts 2 and 3.

Design

Equal numbers of infants participated in three familiarization conditions: continuous, discontinuous and control. Then all the infants were presented with the one-object and two-object test displays on six alternating trials, with the order of displays counterbalanced within each condition.

Procedure

Each infant was seated in front of the stage with the curtain closed. In the two experimental conditions, a familiarization trial began when the curtain opened to reveal one of the occlusion events. The event occurred repeatedly for as long as the infant looked at it. The trial ended with the closing of the curtain when the infant looked away for 2 s continuously, after looking at the event for at least 1 s. Presentations of this event continued until a criterion of habituation was met or until 14 familiarization trials had been administered, whichever came first. The criterion was reached when the sum of looking times on three consecutive trials was less than 50 per cent of the first three consecutive trials for which the sum of looking times exceeded 12 s. After the last familiarization trial, the curtain was closed, the screens were removed, a cylinder was added to or taken from the display, if necessary, and the curtain was opened for the first test trial. The test trials followed the same procedure as the familiarization trials. In the control condition, the experiment consisted of the six test trials. Infants first were familiarized with the experimental situation by participating in a different habituation experiment, in which they viewed displays unrelated to those of the present study.

Two observers recorded looking time by watching the infant through peepholes at the sides of the display. The observers could not see the display and were not informed of the order of test trials. Fixations anywhere within the display area were counted as looks at the event, whether or not the infant was fixating or tracking an object. The observers judged looking time independently by pressing separate push button inputs to a microcomputer. Based on the recording of one observer, the microcomputer signalled the end of each trial, calculated looking time per trial, and determined when the habituation criterion had been met. The microcomputer also calculated the inter-observer agreement: the proportion of seconds on which the two observers agreed that an infant was or was not looking at the display. Inter-observer agreement averaged .85.

Dependent measures and analyses

Because looking times tended to be positively skewed, they were log-transformed for all of the analyses. All means and standard deviations presented in the text, tables and figures are based on log-transformed looking times. For descriptive purposes, the looking preferences of the infants in each condition were analysed by individual *t* tests. To assess the overall effect of the three familiarization conditions on test-trial looking preferences and interactions of this effect with other experimental variables, the test-trial looking times of the infants in the three conditions were analysed by a 3 (condition: continuous, discontinuous and control) by 2 (test-trial order) by 3 (trial pair) by 2 (test display: one-object display vs.

two-object display) analysis of variance with the last two factors within subjects. Finally, in order to assess differences in looking preferences between the test displays across pairs of familiarization conditions, difference scores were calculated for each subject by subtracting the mean of the log-transformed looking times for the two-object display from those of the one-object display. These differences were compared for each pair of familiarization conditions by Bonferroni-corrected *t* tests (Rosenthal & Rosnow, 1991, p. 331).[2]

All reported *t* tests are two-tailed. A measure of effect size, *r*, is reported along with each significance test.[3]

Results

Figure 3 and Table 1 present the principal findings. The infants in each experimental condition met the habituation criterion in an average of 10 trials. All but two infants in each experimental condition met the habituation criterion. After familiarization, infants' preference for the two-object display (over the one-object display) appeared to be highest in the continuous condition, intermediate in the control condition, and lowest in the discontinuous condition. Infants in the continuous condition showed a reliable preference for the two-object display ($t(7) = 3.51$, $p = .010$, $r = .799$), those in the control condition showed a non-significant preference for the two-object display ($t(7) = 1.71$, $p = .131$, $r = .5428$) and those in the discontinuous condition showed a reliable preference for the one-object display ($t(7) = 2.59$, $p = .036$, $r = .700$).

The analysis of variance revealed a significant effect of trial pair ($F(2,36) = 5.97$, $p = .006$, eta = .499), a marginal effect of test display ($F(1,18) = 3.99$, $p = .061$, $r = .426$), a marginal condition × test-trial order × trial pair interaction ($F(4,36) = 2.20$, $p = .089$, eta = .443), and a significant condition × test display interaction ($F(2,18) = 9.89$, $p = .001$, eta = .724).[4]

Over the three test-trial pairs, infants showed a decrease in looking time. Although this decrease interacted somewhat with order and condition, the three-way interaction is sufficiently complex and sufficiently marginal that it does not merit much attention. The marginal main effect of test display, reflecting a small overall preference for the two-object display, is not of theoretical interest. The strong condition × test display interaction is the effect of interest and is analysed further below.

Individual *t* tests comparing the mean difference between the one- and two-object test displays across pairs of conditions revealed that the infants in the discontinuous condition showed reliably different test preferences from those in the continuous condition ($t(14) = 4.36$, $p_{adj.} = .002$, $r = .759$) and from those in the control condition ($t(14) = 2.97$, $p_{adj.} = .030$, $r = .622$). Although the infants in the continuous condition

[2] Given that each test event is situated in an experimental context in which two events are shown, comparisons across conditions of absolute looking times at individual events are not informative. Instead, we must look at changes across conditions in the relative preferences for one test event over another.

[3] According to Rosenthal & Rosnow (1991), 'effect size refers to the strength (or magnitude) of the relationship' (p. 42). Given that significance tests are a function of both the size of the effect and the number of subjects, comparisons of significance levels across conditions with different number of subjects can be misleading. Effect sizes allow comparisons of the magnitude of an effect across conditions. In this case, $r = \text{sqrt}[t^2/(t^2 + \text{d.f.})]$ where d.f. is the degrees of freedom and sqrt is the square root (Rosenthal & Rosnow, 1991).

[4] Eta is a measure of effect size that is comparable to *r*, but applies for omnibus tests which have more than 1 d.f. in the numerator.

$$\text{eta} = \text{sqrt}\{[(F)(df_{num})]/[(F)(df_{num}) + (df_{err})]\}$$

where df_{num} is the degrees of freedom in the numerator of the test and df_{err} is the degrees of freedom for the error term.

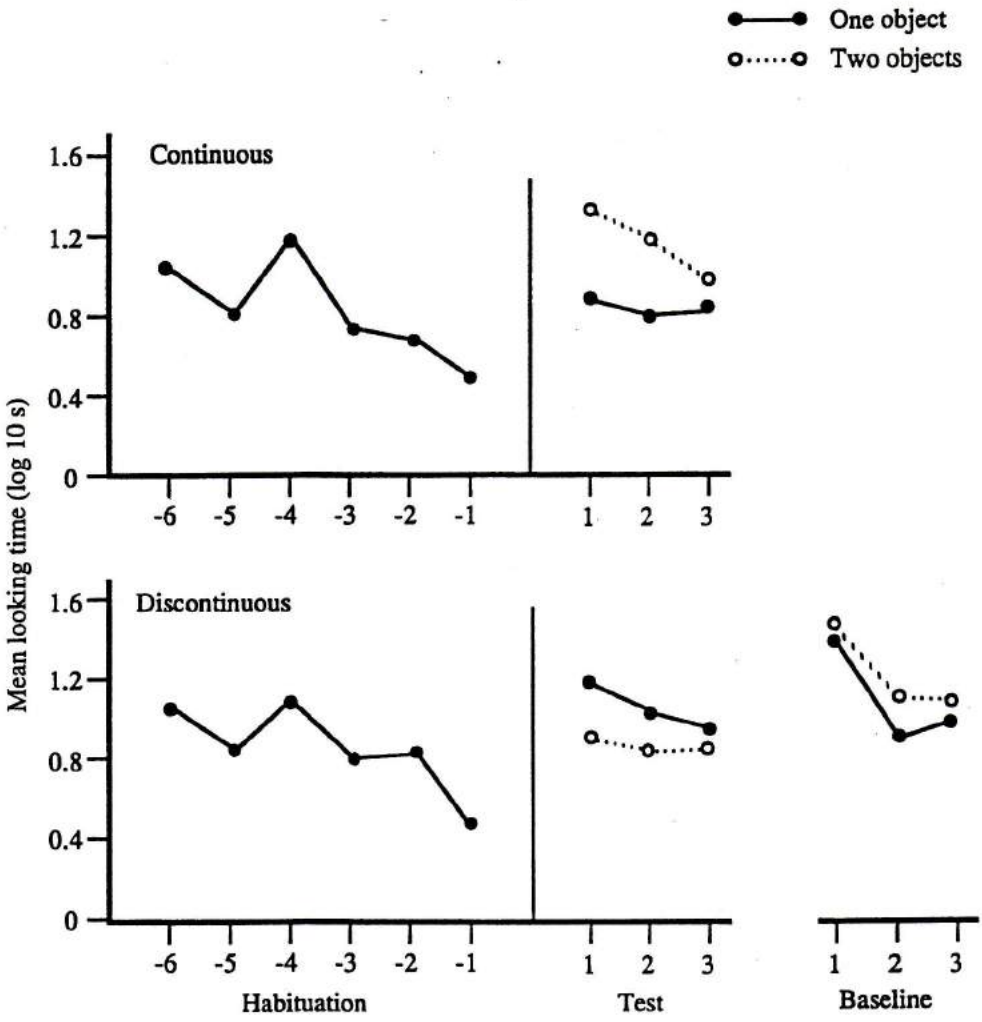

Figure 3. Mean log-transformed looking times during the last six habituation trials and the six test trials in each condition of Expt 1.

tended to show a greater preference for the two-object display than did those in the control condition, this difference was not significant ($t(14) = 1.40, p_{adj.} = .552, r = .350$).

Discussion

Infants in the continuous, discontinuous and control conditions showed reliably different looking preferences between displays of one vs. two objects. Direct comparisons across pairs of conditions revealed that this effect was due primarily to the significant differences between looking preferences in the continuous vs. the discontinuous conditions and between the discontinuous and control conditions. The former difference, in particular, provides evidence that infants' perception of object identity is influenced by the continuity vs. discontinuity of object motion, in accord with the continuity principle.

Table 1. Log-transformed mean (and standard deviations) for Expt 1 by condition, trial pair and test display

Test	Habituation condition		
	Continuous ($N = 8$)	Discontinuous (($N = 8$)	Control ($N = 8$)
Trial pair 1			
1 object	0.88 (0.36)	1.20 (0.38)	1.40 (0.40)
2 objects	1.33 (0.30)	0.90 (0.28)	1.47 (0.62)
Trial pair 2			
1 object	0.80 (0.29)	1.04 (0.41)	0.90 (0.60)
2 objects	1.15 (0.30)	0.85 (0.30)	1.13 (0.52)
Trial pair 3			
1 object	0.87 (0.36)	0.95 (0.47)	0.96 (0.59)
2 objects	1.05 (0.51)	0.87 (0.44)	1.10 (0.45)
Trial pairs 1–3			
Mean 1 object	0.85 (0.27)	1.06 (0.28)	1.08 (0.29)
Mean 2 object	1.18 (0.30)	0.87 (0.29)	1.23 (0.43)
Difference[a]	0.33 (0.26)	−0.19 (0.21)	0.15 (0.25)

[a] In all of the tables, 'difference' refers to the Σ(mean 2−mean 1)/N, which is the average of each subject's difference score. This difference score is calculated by subtracting the mean of the one-object test trials from the mean of the two-object test trials.

This conclusion may be questioned, nevertheless, because of two features of the experiment. First, although the infants in the continuous condition tended to show the greatest preference for the two-object display, the analyses revealed no significant difference between the preferences of the infants in the continuous condition and those in the control condition. The experiment therefore provides no clear evidence that infants in the continuous condition perceived a determinate number of objects during familiarization, as predicted by the thesis that infants perceive object identity in accord with the continuity principle. The number of subjects in the experiment (eight per condition) may not have been sufficient to reveal this effect of continuity.

Second, the test events of Expt 1 presented the same motion patterns as the familiarization events: both the continuous event and the one-object test event involved constant motion traversing the entire display, and both the discontinuous event and the two-object test event involved interrupted motion on the sides of the display. It is possible that test-trial looking times were affected by differences in the spatial or temporal properties of object motion (for example, the presence or absence of motion through the centre of the display), or by differences in the noises accompanying object motion (for example, sustained noise in the continuous and the one-object event, and intermittent noise in the discontinuous and two-object events) rather than by the perceived number of objects in the events.

Accordingly, Expt 2 was undertaken to replicate Expt 1, with two changes in method. First, the test displays presented objects whose motions and noises did not differ with respect to their spatial or temporal properties: in both the one-object and the two-object

displays, motion occurred discontinuously and only on the sides of the display. Second, the experiment was conducted with twice the number of subjects.

EXPERIMENT 2

Method

The method is the same as in Expt 1, except as follows:

Subjects

The 47 participants (22 females and 25 males) ranged in age from 2 months 20 days to 5 months 0 days (mean age, 4 months 5 days). Thirteen additional infants were eliminated from the sample because of fussiness (1) or experimenter error (12).

Displays

The occlusion and test events are depicted in Fig. 4. All the events were the same as in the previous

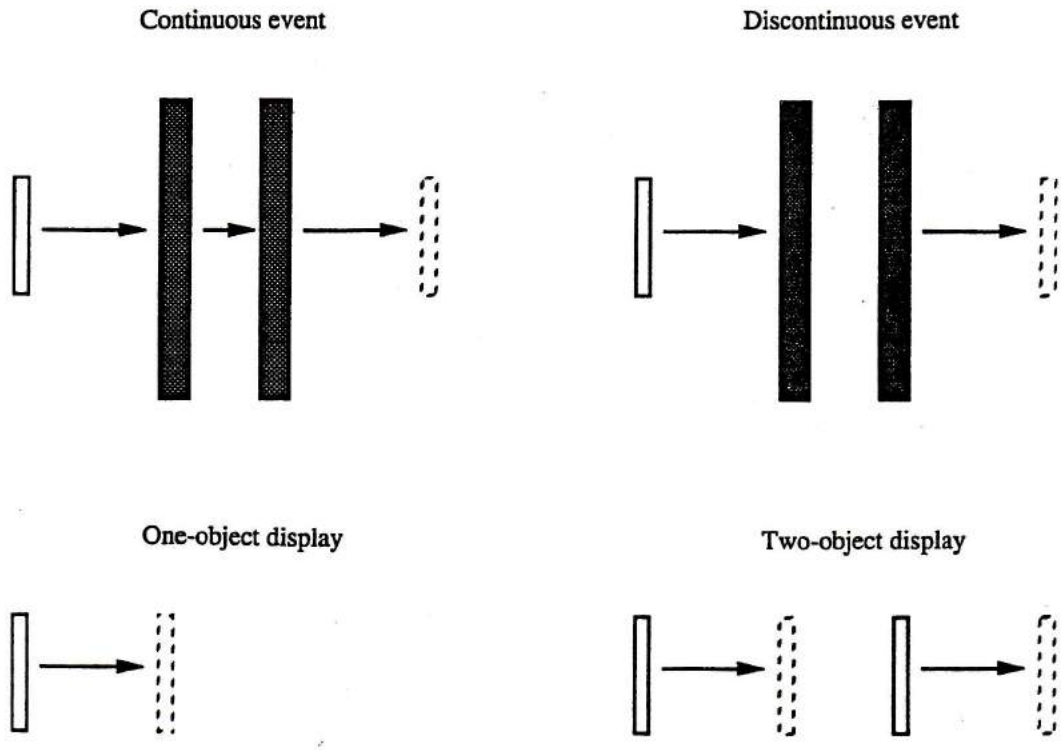

Figure 4. Displays for Expt 2. The one-object test display depicts the event presenting object motion on the left; a second one-object test display (not shown) was the same, except that the object appeared and moved on the right.

experiment except for the one-object test event, which consisted of one cylinder that moved and paused so as to match the motions of the cylinders in the two-object test event and the noise patterns of both events. This cylinder either (*a*) began on the left, moved 23 cm to the right, paused for 2 s, and then

reversed direction or (*b*) began on the right and moved leftward in the same pattern. For each infant, one-object events on the left and on the right were presented in alternation. The two one-object displays therefore presented motions in the same spatial positions and at the same temporal intervals as the two-object display.

Design and procedure

Only the number of subjects in each condition differed from Expt 1. There were 16 subjects in the continuous condition, 16 in the discontinuous condition and 15 in the control condition. Inter-observer agreement averaged .87. The data were analysed as in Expt 1.

Results

Figure 5 and Table 2 present the principal findings. Infants in the experimental

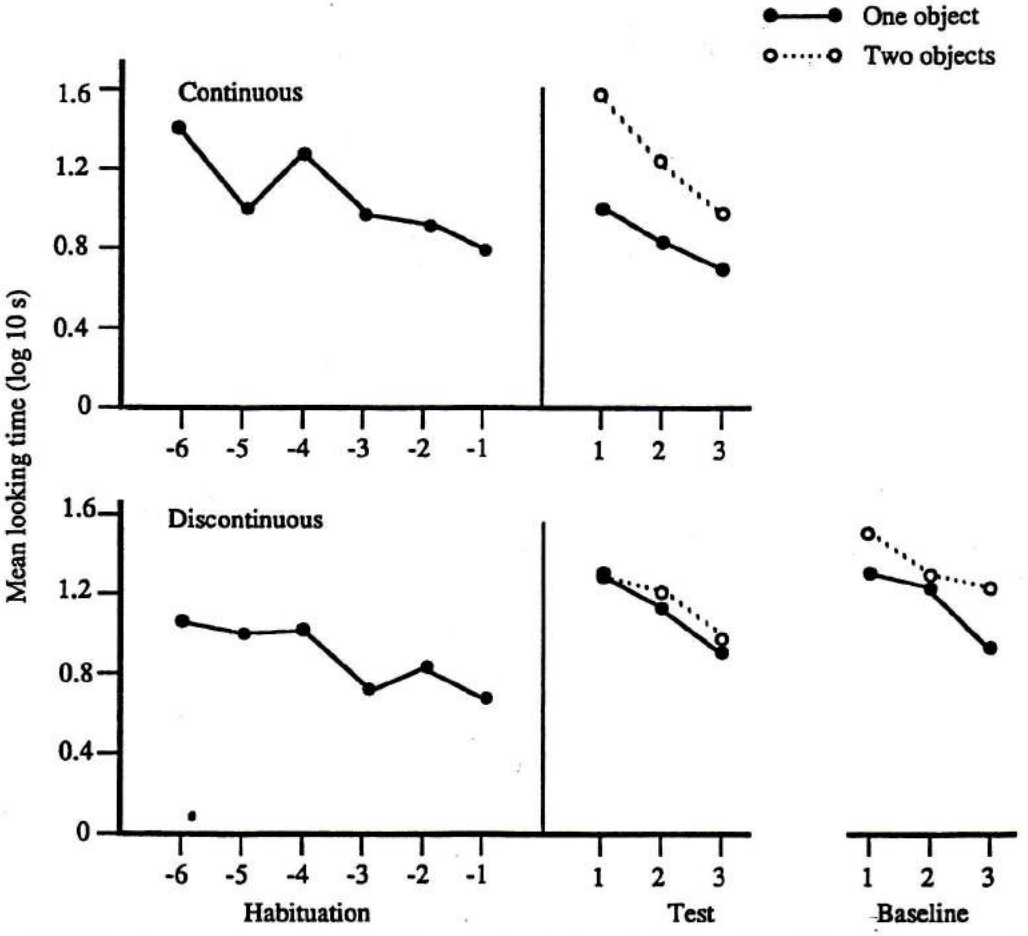

Figure 5. Mean log-transformed looking times during the last six habituation trials and the six test trials in each condition of Expt 2.

conditions met the habituation criterion in an average of nine (continuous condition) or 10 (discontinuous condition) trials. All but three subjects in the continuous condition and five subjects in the discontinuous condition met the habituation criterion. During

Table 2. Log-transformed means (and standard deviations) for Expt 2 by condition, trial pair and test display

Test	Habituation condition		
	Continuous ($N = 16$)	Discontinuous ($N = 16$)	Control ($N = 15$)
Trial pair 1			
1 object	0.99 (0.42)	1.30 (0.40)	1.33 (0.42)
2 objects	1.53 (0.46)	1.33 (0.39)	1.53 (0.48)
Trial pair 2			
1 object	0.81 (0.35)	1.12 (0.36)	1.15 (0.50)
2 objects	1.24 (0.46)	1.23 (0.40)	1.33 (0.42)
Trial pair 3			
1 object	0.68 (0.37)	0.95 (0.53)	0.97 (0.29)
2 objects	0.97 (0.36)	1.01 (0.28)	1.17 (0.46)
Trial pairs 1–3			
Mean 1 object	0.83 (0.29)	1.12 (0.31)	1.15 (0.33)
Mean 2 objects	1.24 (0.26)	1.19 (0.24)	1.34 (0.31)
Difference (2 − 1)	0.42 (0.26)	0.07 (0.30)	0.19 (0.22)

the test, infants in all three conditions looked longer at the two-object test display. As in Expt 1, however, the preference for the two-object display was greatest for those in the continuous condition ($t(15) = 6.51$, $p = .00001$, $r = .859$), intermediate for those in the control condition ($t(14) = 3.35$, $p = .0048$, $r = .667$) and least for those in the discontinuous condition ($t(15) = .94$, $p = .364$, $r = .236$).

The analysis of variance revealed a significant main effect of trial pair ($F(2,82) = 22.56$, $MS_{error} = 0.15$, $p < .0001$, eta = .596), a significant main effect of test display ($F(1,41) = 35.79$, $MS_{error} = 0.10$, $p < .0001$, $r = .683$), a marginally significant test-trial order × test display interaction ($F(1,41) = 3.94$, $MS_{error} = 0.10$, $p = .054$, $r = .296$), and a significant condition × test display interaction ($F(2,41) = 7.64$, $MS_{errpr} = 0.10$, $p = .002$, eta = .521). The first two main effects indicate that looking time decreased over trials, and that there was a general preference for the two-object test display. As in Expt 1, these effects are not of theoretical interest. The first interaction revealed that infants' preference for the two-object display was somewhat accentuated when the two-object display was shown first. Given that this pattern did not differ across conditions, it is of little interest. Finally, the second interaction revealed that infants in the three familiarization conditions showed different looking preferences between the test displays; this interaction is of principal interest and is analysed further.

Individual t tests comparing the mean differences between looking times at the one- vs. two-object test displays across the different conditions revealed that the infants in the continuous condition showed a greater preference for the two-object display than did those in the discontinuous condition ($t(30) = 3.55$, $p_{adj.} = .0039$, $r = .544$) and those in the control condition ($t(29) = 2.68$, $p_{adj.} = .036$, $r = .446$ (see footnote 2). Although the

infants in the control condition tended to show a greater preference for the two-object display than those in the discontinuous condition, this difference was not significant ($t(29) = 1.26$, $p_{adj.} = .653$, $r = .228$).

Discussion

As in Expt 1, infants who were familiarized with continuous motion showed reliably different preferences for the one-object vs. two-object test displays than did those who were familiarized with discontinuous motion. This difference cannot be attributed to artifactual differences in the temporal pattern of motion presented to infants or to differences in the pattern of noises that the moving objects produced, because the two test displays in this experiment presented the same temporal patterns of motion and noise. The experiment therefore provides evidence that 4-month-old infants' apprehension of object identity is affected by the spatiotemporal continuity of object motion.

Both in Expt 1 and in Expt 2, the ordering of preferences in the continuous, discontinuous and control conditions tends to support the claim that infants in the continuous condition perceived one object during habituation and that those in the discontinuous condition perceived two objects. Nevertheless, the difference in preferences between the continuous and control conditions was significant only in Expt 2, and the difference in preferences between the discontinuous and control conditions was significant only in Expt 1. This change in the pattern of group differences may stem from the fact that the infants in the control condition of Expt 2 showed a slightly larger preference for the two-object display than did those in Expt 1.

In view of the weak and unstable differences between the experimental and control conditions in Expts 1 and 2, no strong conclusions can be drawn concerning the number of objects infants perceived in a given occlusion display. Both experiments nevertheless provide clear evidence that infants' perception of object identity differed reliably in the continuous and discontinuous conditions, in accord with the continuity principle.

Together, Expts 1 and 2 suggest a dissociation between the capacities underlying perception of object identity and the capacities underlying visual tracking and search. At 5 months of age, visual tracking is unaffected by the continuity or discontinuity of object motion, when infants are presented with nearly the same events as in the present studies (Moore *et al.*, 1978). One possible account of the different findings of search experiments and preferential looking experiments is that preferential looking methods are more sensitive than visual search methods: both visual search and preferential looking may be guided by the same mechanisms for perceiving and individuating objects, but those mechanisms may function more effectively in preferential looking tasks. A second possible account of this difference is that preferential looking at novel events is guided by different mechanisms than visual search for moving objects, and that the two sets of mechanisms are sensitive to different constraints on objects.

One way to distinguish between these possibilities is to investigate whether infants tested in preferential looking experiments perceive object identity in accord with the smoothness principle. Recall that infants' visual search for objects accords with this principle: search is disrupted when infants are presented with events that violate this principle (Bower *et al.*, 1971; Moore *et al.*, 1978). If preferential looking and visual search are guided by the same constraints on objects, and if preferential looking methods reveal

infants' sensitivity to these constraints more clearly, then infants' perception of object identity, assessed by the present method, should be affected by the smoothness of object motion. In contrast, if preferential looking and visual search are guided by different constraints on objects, then infants' perception of object identity in preferential looking experiments may not be affected by the smoothness of object motion. Such a finding would accord with other research suggesting that infants' inferences about the motions and the resting position of a hidden object are unaffected by the smoothness principle (Spelke *et al.*, 1994; Spelke, Simmons, Breinlinger, Jacobson & Macomber, submitted). The next experiments accordingly used the method of Expts 1 and 2, and events similar to those of Moore *et al.* (1978), to investigate whether infants perceive object identity by analysing the smoothness of object motion.

Experiment 3 focused on infants' perception of an event in which an object moves visibly at a constant speed, disappears behind one side of a wide screen, and reappears at the opposite side of the screen after a duration of occlusion that is appropriate to the object's visible motion. Although adults were not found to have a strong or consistent impression of a single object in this event (see Appendix), studies of visual tracking provide evidence that infants follow the object in this event smoothly: a pattern consistent with the thesis that infants perceive a single object moving behind the occluder (Bower *et al.*, 1971; Moore *et al.*, 1978).

EXPERIMENT 3

Infants were repeatedly presented with an event in which an object moved back and forth at a constant speed behind one wide screen (Fig. 6). To investigate their apprehension of object identity, infants were then presented with the one- and two-object test displays of Expt 1, and their looking times were compared to the looking times of the infants in the control condition of Expt 1. If infants perceive object identity by maximizing the smoothness of object motion, then the infants in Expt 3 should have perceived a single object in the occlusion event. Habituation to this event therefore should generalize to the one-object display, producing a looking preference for the two-object display, relative to controls. In contrast, if infants perceive object identity in accord with the continuity principle but not the smoothness principle, then the infants in Expt 3 should not have perceived a determinate number of objects in the occlusion event. Because the screen was wide enough easily to accommodate two objects, either one or two persisting and continuous movable objects could have participated in this occlusion event. The infants in the experimental and control conditions therefore should exhibit the same looking preference between the one- and two-object test events.

Method

The method was the same as that of Expt 1, except as follows:

Subjects

The eight participants (six girls and two boys) ranged in age from 3 months 15 days to 4 months 29 days (mean age, 4 months 0 days). One additional subject was eliminated from the sample because of experimenter error.

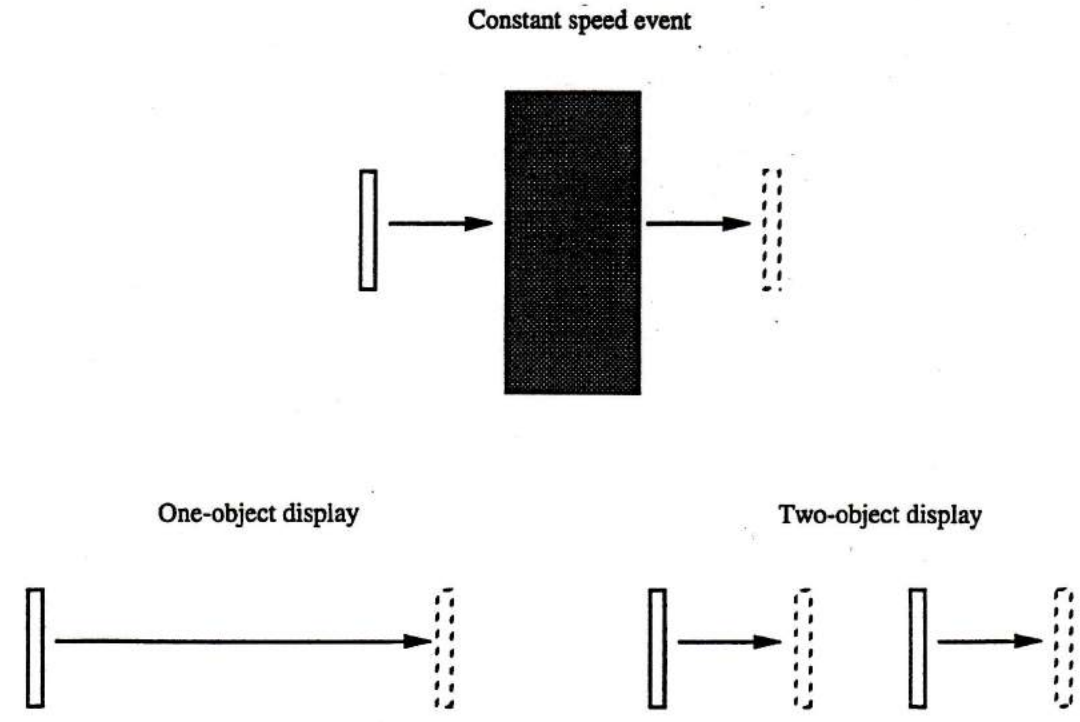

Figure 6. Displays for Expt 3.

Displays

The occlusion event consisted of one visible cylinder and one wide screen. The cylinder was the same as in Expts 1 and 2. The screen was the same as the screens in the previous experiments except for its width of 20 cm (17.2°): it corresponded in size to the narrow screens plus the space between them. The cylinder moved as in the occlusion events of Expts 1 and 2, disappearing behind the wide screen for 2.4 s. The one- and the two-object displays were the same as in Expt 1.

A tape-recording of motor noise was played throughout the events to mask the sounds of the motor-driven apparatus. As an additional control for the effects of motor noise, half the infants in Expt 3 were presented with one cylinder moving behind the screen as the cylinder moved in the one-object test display, and half the infants were presented with two cylinders moving behind the screen as the cylinders moved in the two-object test display. These two displays were visually indistinguishable when the occluder was in place.

Design and procedure

Equal numbers of subjects were familiarized with the occlusion event produced with one vs. two objects. After familiarization, infants were presented with the same test displays as in Expt 1. Test-trial looking times were compared to those of infants in the control condition of Expt 1. Inter-observer agreement averaged .87.

Results

Figure 7 and Table 3 present the principal findings of this experiment; the findings of the corresponding control condition are given in Fig. 3 and Table 1. Infants met the criterion of habituation in a mean of 10 trials. Three of the infants in the experimental condition

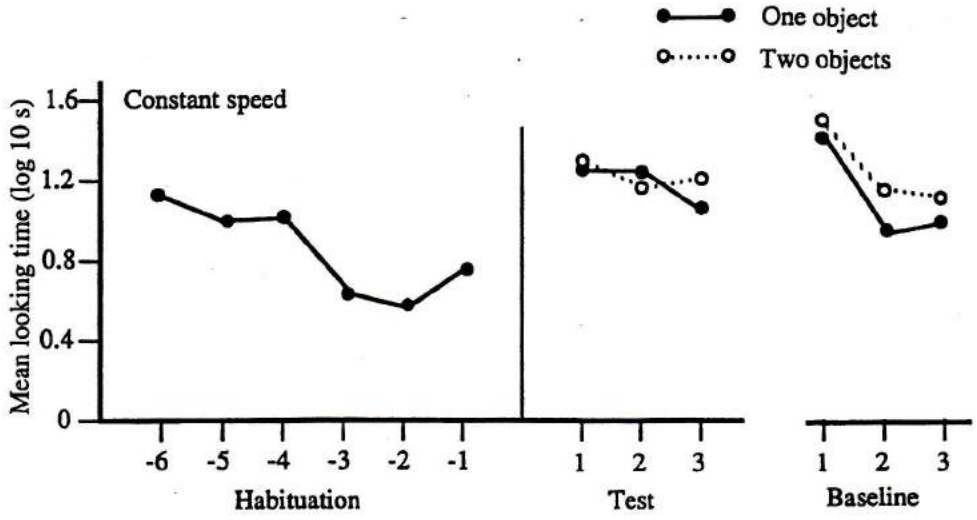

Figure 7. Mean log-transformed looking times during the last six habituation trials and the six test trials in Expt 3 (left) and during the six test trials in the control condition of Expt 1 (right).

Table 3. Log-transformed means (and standard deviations) for Expt 3 by condition, trial pair and test display

Test	Habituation condition	
	Experimental ($N = 8$)	Control (from Expt 1) ($N = 8$)
Trial pair 1		
1 object	1.28 (0.59)	1.40 (0.40)
2 objects	1.29 (0.40)	1.47 (0.62)
Trial pair 2		
1 object	1.26 (0.48)	0.90 (0.60)
2 objects	1.16 (0.60)	1.13 (0.52)
Trial pair 3		
1 object	1.05 (0.59)	0.96 (0.59)
2 objects	1.21 (0.53)	1.10 (0.45)
Trial pairs 1–3		
Mean 1 object	1.20 (0.41)	1.08 (0.29)
Mean 2 objects	1.22 (0.33)	1.23 (0.43)
Difference (2 − 1)	0.02 (0.39)	0.15 (0.25)

failed to meet the habituation criterion. During the test, infants in the experimental condition showed little preference for one test display over the other ($t(7) = .16$, $p = .877$, $r = .060$). The reader may recall that infants in the control condition looked longer at the two-object display, but this preference did not reach significance ($t(7) = 1.71$, $p =$

.131, $r = .543$). The $2 \times 2 \times 3 \times 2$ analysis of variance, performed on the data obtained in the present experiment and in the control condition of Expt 1, revealed no significant effects (all $Fs<2.6$, all $ps>.10$). Notably, the condition × test display interaction was not significant ($F(1,10) = 0.78$, $MS_{error} = 0.20$, $p = .397$, $r = .269$).

A separate analysis of motor noise tested differences in looking times between the test displays when the occlusion events were produced with one vs. two objects. This 2 (number of objects in the familiarization event: one vs. two) × 2 (test display) ANOVA produced no significant results (all $Fs<1$). Nevertheless, the infants familiarized with the occlusion event produced with one object showed slightly lower looking times to the one-object display ($M = 1.121$, SD = 0.534) than to the two-object display ($M = 1.213$, SD = 0.162), and those familiarized with the occlusion event produced with two objects showed slightly lower looking times to the two-object display ($M = 1.229$, SD = 0.478) than to the one-object display ($M = 1.276$, SD = 0.412).

Discussion

After habituating to an occlusion event in which an object moved at a constant speed, infants' looking preference between events involving one vs. two visible objects did not differ from control levels. The experiment therefore provides no evidence that infants used the smoothness principle to perceive a determinate number of objects in the original event. These negative findings accord with adults' ratings of the constant speed event: adults did not judge consistently that the event involved one or two objects.

It is unlikely that the negative findings of this study resulted from the small sample size of the experiment, because the trends in the data were not in the correct direction. If the smoothness of object motion influenced infants' apprehension of object identity, then the infants in the present study should have looked longer at the two-object display, relative to controls. In fact, the looking preference for the two-object display was non-significantly larger for the control group than for the experimental group (see Table 3).

The results of the analysis comparing the test preferences of infants familiarized with the event produced with one object and that produced with two objects suggest that the masked motor noises had little effect on infants' preferences. Because the means were in the direction of such an effect, however, it would be prudent for investigators to equate for the patterns of motor noise (as we did in Expt 2).

The present experiment is limited in two respects. First, the occlusion event involved a slowly moving object. It is possible that infants (and adults) would have perceived a single object in this event if the occlusion time had been reduced by increasing the object's speed. Second, the experiment did not investigate what infants perceive when a moving object is occluded for an inappropriate duration, as if its speed changed spontaneously while it was hidden. Experiment 4 addressed these limitations. It presented events with briefer occlusion times, and it investigated whether variations in the appropriateness or inappropriateness of an object's occlusion time affect infants' apprehension of object identity.

EXPERIMENT 4

The events for Expt 4 were again modelled on events used in studies of visual tracking (Moore *et al.*, 1978). Four-month-old infants viewed an object that moved visibly at a

constant speed on the two sides of a wide screen. Separate groups of infants were presented with a *constant speed event*, in which the object was occluded for an appropriate duration, a *changed speed event*, in which the object was occluded for an inappropriately brief duration, and an *immediate reappearance event*, in which the object's occlusion time was extremely brief. All the infants, as well as infants in a control condition, were then tested with the displays of one vs. two fully visible objects. If information for the constancy or change of object speed influences infants' apprehension of object identity, the looking preferences between the test displays should differ among the four conditions. Infants familiarized with the immediate reappearance and the changed speed events should look longer at the one-object display, relative both to infants in the control condition and to infants familiarized with the constant speed event.

Although it is not possible to vary the appropriateness of an object's occlusion time relative to its speed while holding constant both the duration of time that the object is occluded and the speed at which it moves when it is visible, it is important to assure that differences in test preferences are not attributable to variations in the latter two factors. Accordingly, two experimental conditions in this study presented events that equated for duration of occlusion (the constant speed and changed speed events), and two experimental conditions presented events that equated for the speed of visible motion (the changed speed and immediate reappearance events). Comparing the looking preferences of infants in different conditions should therefore reveal whether any differences in preferences between the test displays are attributable to the smoothness of object motion, to variations in object speed or to variations in occlusion time.

Adult subjects, presented with the familiarization events of Expt 4, judged that a single object participated in the constant speed event, and they gave no consistent judgement of the number of objects in the changed speed and immediate reappearance events (see Appendix). Direct comparisons of judgements for these three events revealed significant effects of the appropriateness vs. inappropriateness of occlusion time on adults' judged impressions of numerical identity. Comparisons with the judgements for the events from Expts 1 and 2 suggested, nevertheless, that impressions of numerical identity were weaker and less consistent for the present events than for the events presenting continuous vs. discontinuous motion.

Method

The displays and procedure were the same as in Expts 1 and 2, except as follows:

Subjects

The 32 participants (16 females and 16 males) ranged in age from 3 months 14 days to 4 months 27 days (mean age, 4 months 4 days). Eight additional infants were eliminated from the sample because of fussiness (2) or experimenter error (6).

Displays

The occlusion events consisted of two wider cylinders moving successively behind the wide screen from Expt 3. The 19 cm long, 7 cm diameter cylinders each subtended 15.0° by 5.6° at the infant's point of observation. They were painted as in the previous experiments, and they were suspended and moved in the same manner.

In all the occlusion events, one cylinder began on the left of the display, moved 25 cm to the right, and then stopped when it was fully hidden behind the screen. After a pause of a specified duration, the second cylinder, which had been resting behind the other side of the screen, moved into view and continued moving rightward for 25 cm. Then the second cylinder reversed direction and the event was repeated with leftward motion. Because two cylinders were used in all the events, including the constant speed event, all these events presented discontinuous patterns of motor noise.

In the constant speed event, the speed of visible motion was 11.3 cm/s (9.0°/s) and the occlusion time was 1.2 s. This event is equivalent to one in which an object moves at the constant speed of 11.3 cm/s. In the changed speed event, the speed of visible motion was 3.5 cm/s (2.8°/s) and the occlusion time was 1.2 s. This event is equivalent to one in which an object moves at the rate of 3.5 cm/s when it is visible but more than triples its average speed (to 11.3 cm/s) when it is hidden. In the immediate reappearance event, the speed of visible motion was 3.5 cm/s and the occlusion time was less than 1 s: the second cylinder appeared as soon as the first cylinder was fully hidden.

The test displays were the same as those for Expts 1 and 3, except that the wide cylinders were used. As in the previous studies, the cylinders moved at the rate of 7.4 cm/s, with 2 s pause in the two-object display.

Design and procedure

Equal numbers of infants participated in the constant speed, changed speed, immediate reappearance and control conditions. Inter-observer agreement averaged .87.

Results

Figure 8 and Table 4 present the principal findings. Infants in the experimental conditions met the habituation criterion in an average of eight (constant speed and changed speed conditions) or nine (immediate reappearance condition) trials. Two subjects in the immediate reappearance condition and two in the changed speed condition failed to meet the habituation criterion. During the test, the infants in all four conditions showed a preference for the two-object display. This preference was strongest for the control condition ($t(7) = 3.11$, $p = .017$, $r = .762$) and the constant speed condition ($t(7) = 2.36$, $p = .050$, $r = .666$); it was weaker and only marginally significant for the immediate reappearance condition ($t(7) = 1.86$, $p = .105$, $r = .575$) and it was weakest and not significant for the changed speed condition ($t(7) = 0.27$, $p = .795$, $r = .102$).

A $4 \times 2 \times 3 \times 2$ analysis of variance revealed main effects of trial pair ($F(2,48) = 8.71$, $MS_{error} = 0.18$, $p = .001$, eta = .516) and of test display ($F(1,24) = 14.01$, $MS_{error} = 0.11$, $p = .001$, $r = .607$). Looking times declined over successive pairs of trials, and looking times were higher for the two-object display. No other effects were significant, including the condition × test display interaction ($F(3,24) = 1.21$, $MS_{error} = 0.11$, $p = .328$, eta = .362).

Finally, individual t tests compared the looking preferences for the two-object test display (relative to the one-object display) across the different conditions. None of the experimental groups' preferences differed significantly from the preference of the control group or from each other (all $ts<2$, all $p_{adj.}s>.40$, all $rs<.45$).

Discussion

After habituating to any of three events in which an object moved out of view and an object returned to view behind a single wide occluder, 4-month-old infants showed

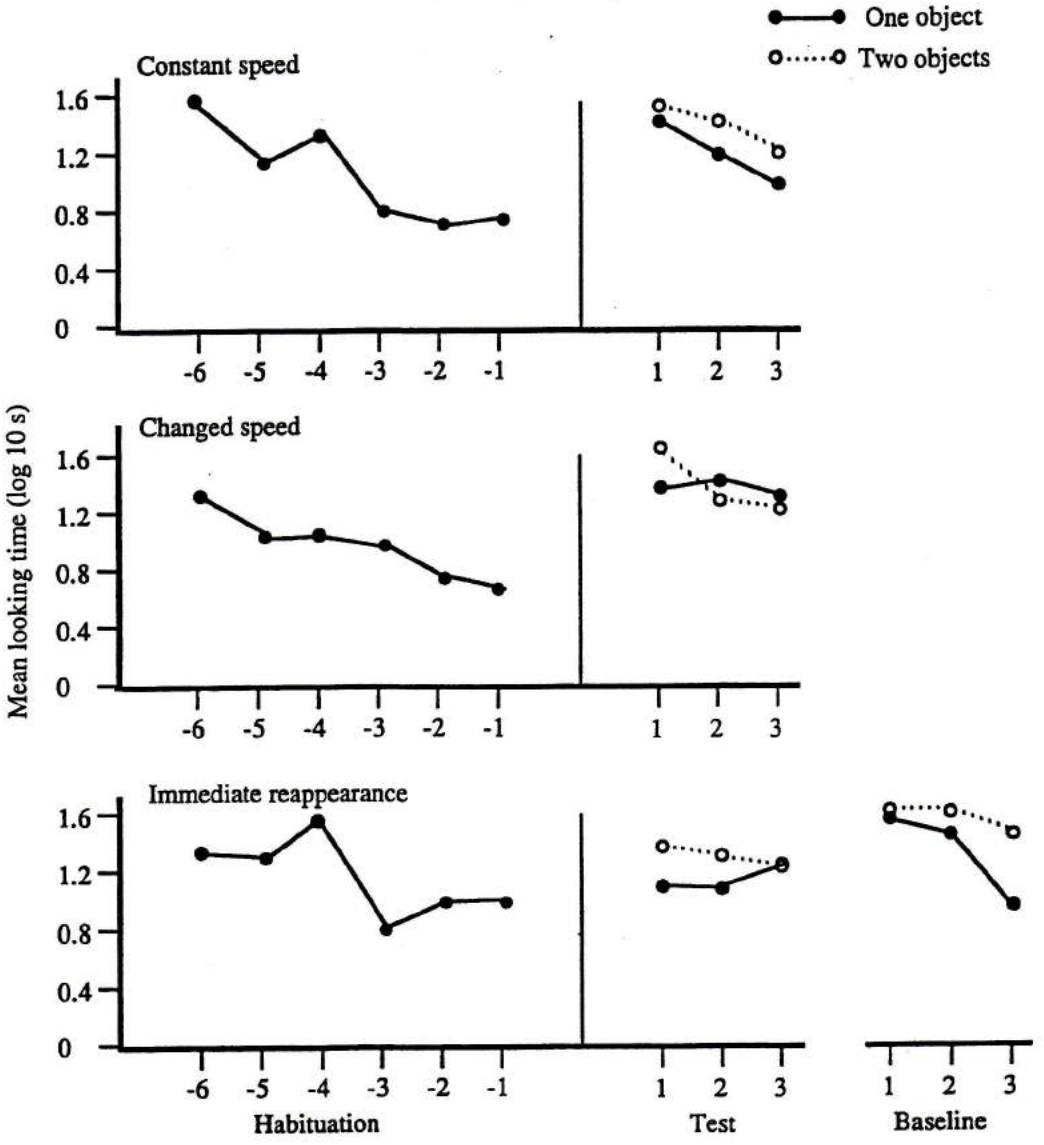

Figure 8. Mean log-transformed looking times during the last six habituation trials and the six test trials in each condition of Expt 4.

similar looking preferences for a display of two objects as did a group of infants who saw none of the familiarization events. Test-trial looking preferences were not significantly affected by the apparent smoothness of object motion; the non-significant trends in the data were opposite in direction to those expected if infants perceived one object in the constant speed event and two objects in the two events with inappropriately brief occlusion times. The absence of differences across conditions also suggests that looking times were not strongly affected by the factors that were partially confounded with the smoothness-of-motion factor: the speed of object motion and the duration of occlusion. Experiment 4 therefore provides no evidence that young infants apprehend object identity in accord with the smoothness principle.

Table 4. Log-transformed means (and standard deviations) for Expt 4 by condition, trial pair and test display

Test	Habituation condition			
	Constant speed ($N = 8$)	Changed speed ($N = 8$)	Immediate reappearance ($N = 8$)	Control ($N = 8$)
Trial pair 1				
1 object	1.43 (0.59)	1.37 (0.39)	1.12 (0.71)	1.57 (0.38)
2 objects	1.57 (0.48)	1.70 (0.47)	1.49 (0.53)	1.62 (0.59)
Trial pair 2				
1 object	1.17 (0.47)	1.38 (0.58)	1.13 (0.44)	1.30 (0.61)
2 objects	1.46 (0.43)	1.24 (0.67)	1.41 (0.51)	1.61 (0.40)
Trial pair 3				
1 object	0.94 (0.50)	1.27 (0.44)	1.28 (0.56)	0.90 (0.34)
2 objects	1.19 (0.48)	1.16 (0.40)	1.26 (0.41)	1.34 (0.55)
Trial pairs 1–3				
Mean 1 object	1.18 (0.43)	1.34 (0.37)	1.18 (0.39)	1.26 (0.40)
Mean 2 objects	1.41 (0.31)	1.37 (0.43)	1.38 (0.40)	1.52 (0.34)
Difference (2 − 1)	0.23 (0.27)	0.03 (0.27)	0.21 (0.32)	0.27 (0.24)

The present findings cast doubt on the view that preferential looking methods are more sensitive than visual tracking methods as measures of infants' processing of object motion. Although visual tracking of events very similar to those of Expt 4 is affected reliably by the constancy or change in speed of object motion, infants' perception of object identity in the present study showed no such effect. These findings, together with the findings of Expts 1 and 2, provide evidence that different constraints on objects guide infants' perception of object identity in preferential looking experiments and infants' visual tracking and search for objects.

Infant's preferential looking patterns failed to accord with the ratings of adult subjects, whose judged impressions of the number of objects in the occlusion events were affected reliably by the apparent smoothness of object motion. Nevertheless, adults' rated impressions of object identity agreed with infants' looking patterns in two respects. First, adults reported no determinate impression of two objects in the events with inappropriate occlusion time. Second, adults' impressions of numerical identity were significantly weaker for the events in the present study than for those of Expts 1 and 2. Both for infants and for adults, apprehension of object identity may be influenced more by the continuity of object motion than by the smoothness of object motion.

GENERAL DISCUSSION

Experiments 1 and 2 provide evidence that 4-month-old infants' perception of object identity over occlusion is reliably affected by information for the continuity or discontinuity of object motion. In two experiments, perception of a single object moving in and out of view, as evidenced by a preference for a test display of two objects, was

stronger when the occluded object's motion was continuous than when it was discontinous. Although preferences for the two-object display did not differ consistently from control levels over the two experiments, the trends in the data from both experiments suggest that infants perceived a single object in the continuous event and two objects in the discontinuous event. The findings obtained in the experimental conditions provide evidence that infants, like adults, apprehend object identity in accord with the continuity principle. The trends obtained in the comparisons between the experimental and control conditions are consistent with this suggestion, although they do not justify any strong conclusions concerning the number of objects that infants perceive in a single experimental condition of Expts 1 and 2.

In contrast, Expts 3 and 4 provide no evidence that 4-month-old infants apprehend object identity by analysing the smoothness of object motion. When objects moved visibly at a constant speed and were occluded for an appropriate duration, infants did not appear to apprehend a single object moving behind the occluder. Infants' perception of object number appeared to be indeterminate, regardless of the speed of object motion (rapid in the constant speed event of Expt 4, slow in Expt 3) and the duration of occlusion (long in Expt 3, shorter in Expt 4). Moreover, when objects moved visibly at a constant speed and were occluded for an inappropriate duration, infants did not appear to perceive two distinct objects moving in and out of view. The tendency to perceive two objects was no stronger when the object's occlusion time was inappropriate to its visible speed than when it was appropriate to that speed. These findings cast doubt on the thesis that the smoothness principle guides infants' apprehension of object identity over occlusion.

Any negative conclusion must be viewed with caution. Future experiments, using different types of events or a different method, might reveal that infants can apprehend object identity by analysing the smoothness of object motion. The present method and events were sufficient, nevertheless, to reveal consistent effects of spatiotemporal continuity on infants' apprehension of object identity. The principle that objects move on connected paths appears to be more powerful for infants than the principle that objects move at smoothly changing speeds.

Object identity and object search

The present conclusions are opposite to those drawn from studies of visual search for objects: whereas 4-month-old infants' perception of object identity accords with the continuity principle but not the smoothness principle, 5-month-old infants' visual tracking of closely similar events accords with the smoothness principle but not the continuity principle (Moore *et al.*, 1978). It is unlikely that these differences reflect differences in the ages of the babies in the experiments, because visual tracking in accord with the smoothness principle and in violation of the continuity principle has been reported at younger ages as well (Bower *et al.*, 1971). The constraints that guide perception of object identity and tracking of object motion therefore differ qualitatively.

Studies by Moore *et al.* (1978) and by Xu & Carey (1992) suggest a further qualitative difference between infants' perception of object identity and infants' patterns of visual search. In a condition of the Moore *et al.* (1978) experiment that we have not yet described, infants were presented with events in which one object moved behind a wide screen and a second object, with a different colour and shape, emerged from behind the

opposite side of the screen. Although 5-month-old infants' visual tracking was not affected by the continuity of object motion, it was affected by this change in object features: infants showed more disruptions of tracking when the event involved objects of different colours and shapes than when the event involved objects of the same colour and shape. This finding suggests that visual search is guided by the principle that a moving object maintains a constant shape and colouring. In contrast, Xu & Carey (1992) used a preferential looking method to investigate older infants' perception of the identity or distinctness of objects in occlusion events similar to those of Moore *et al.* (1978). Infants were found to perceive object identity by analysing the continuity of object motion but not by analysing the sameness or difference in object shape and colour. These findings accord with the present experiments and contrast with those of Moore *et al.* (1978). Like the present studies, Xu & Carey's experiments suggest a double dissociation between the constraints on objects that guide perception of the identity or distinctness of observed objects and the constraints that guide visual tracking.

These dissociations cast doubt on the view that visual search and preferential looking depend on a single mechanism for individuating objects, operating in accord with a single set of principles. Even a multilevelled conception of object identity, developing in an orderly manner such that infants master principles governing the behaviour of objects at one conceptual level and then master the same principles at a higher level (e.g. Piaget, 1976; Rozin, 1976), cannot reconcile the findings of Moore *et al.* (1978) with those of Xu & Carey (1992) or of the present studies. These findings could only be reconciled with the thesis that a single, multilevelled system of knowledge underlies infants' perceptions and actions by proposing that representations at different levels contradict one another directly, and that development brings losses as well as gains in knowledge.

In contrast to the above views, we suggest that infants' ability to perceive object identity over occlusion, as assessed in preferential looking tasks, and to track objects visually, as assessed in visual search tasks, do not draw on a single system of knowledge. At present, studies of cognition in infancy appear to be consistent with at least two characterizations of the knowledge underlying visual search. First, infants' patterns of visual search may not depend on any knowledge of objects and their motions; developmental change in search patterns may reflect developmental changes in infants' action capacities and skills. In particular, young infants' visual search patterns in the experiments of Bower *et al.* (1971) and Moore *et al.* (1978) may not depend on a conception of objects as smoothly movable but on a motor skill for tracking smoothly moving objects, developed either over infants' normal experience with objects or over the course of the initial test trials in which a smoothly moving object appeared repeatedly. This explanation gains plausibility from findings that young infants readily learn spatiotemporal rules for locating objects (Haith, 1993), and it is compatible with a variety of analyses of manual search patterns (see Cornell, 1979; Harris, 1987; Wellman *et al.*, 1986). Developmental changes in visual and manual search patterns need not reflect developmental changes in conceptions of physical objects.

Second, there may be object representations that underlie infants' visual search, but these representations may be functionally separate from the representations guiding infants' perception of object identity in events that infants observe with minimal overt action. In Fodor's (1983) terms, visual tracking and preferential looking each may depend on modular mechanisms, whose internal representations are not constructed on

the basis of all the infant's knowledge and are not available to guide all the infant's actions. The view that visual search depends on a modular mechanism gains plausibility from the findings of studies of infants' reaching for moving objects. Young infants appear to reach for moving objects in accord with the smoothness principle (von Hofsten, 1980). Their reaching patterns cannot easily be explained in terms of learned motor skills (see von Hofsten, 1983) or in terms of spatiotemporal expectations that arise over the course of an experiment (von Hofsten, Spelke, Vishton & Feng, 1993). If visual search also depends on a modular process for extrapolating object motion, then developmental changes in search may stem, in part, from an increasing ability to relate separate cognitive processes to one another (Karmiloff-Smith, 1992; Rozin, 1976).

Object identity and physical knowledge

The present findings accord with those of a number of experiments using preferential looking methods to assess the early development of physical knowledge. As noted in the introduction, a variety of experiments provide evidence that infants extrapolate the motions of hidden objects on paths that are continuous and unobstructed, in accord with the continuity principle (e.g. Baillargeon, 1986; Baillargeon *et al.*, 1990; Leslie, 1991; Spelke *et al.*, 1992, 1994; Wynn, 1992). In addition, some experiments suggest that young infants do not extrapolate the motions of hidden objects on paths that are linear, in accord with the smoothness principle (Spelke *et al.*, 1994). This convergence of findings suggests that a single system of knowledge underlies infants' perception of object identity and infants' inferences about a hidden object's position and motion.[5]

The present experiments also suggest that the ability to apprehend object identity undergoes developmental change. When adults were shown the present events and were asked explicitly about the number of objects that produced them, their judgements were affected systematically both by the continuity principle and by the smoothness principle. More deeply, however, the findings with infants and with adults were similar. The events for which infants most clearly apprehended object identity were those for which adults' identity judgements were strongest and most consistent. Both infants and adults apprehended object identity primarily in accord with the principle that an object moves on one connected path.

This comparison suggests that infants' conception of objects, as revealed by their

[5] Findings that partly conflict with this generalization have, however, emerged from experiments by Baillargeon & Graber (1987) and Baillargeon & DeVos (1991). Infants aged 4–6 months were presented with two occlusion events similar to the constant speed events of Expts 3 and 4. In those events, either a short object or a tall object moved at a constant speed behind a tall screen. After infants were familiarized with the events, they were presented with a screen with a shorter centre, above which the taller object would have been visible if it had moved behind the screen in a rigid translation. When infants were shown the same events with the new occluder, and with no object appearing in the centre of the screen, they looked longer at the event involving the taller object. The investigators reasoned that the infants had apprehended one object in each of the original occlusion events, and that they had represented the hidden object as moving continuously while maintaining a constant height and orientation. The infants were surprised, therefore, when the taller object failed to appear in the centre of the second screen. Baillargeon & Graber's interpretation implies that infants reasoned about the occluded object's motion in accord with the continuity principle, consistent with the present findings. Their interpretation also implies, however, that infants apprehended a single object in each of the original occlusion events, perhaps by maximizing the smoothness of object motion. Control experiments in which infants first were shown two distinct tall or short objects supported this interpretation (see Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987). It is not clear whether the discrepancy between these findings and the findings of Expts 3 and 4 stems from differences in the experimental task or displays. In any case, this discrepancy underscores the need for caution in interpreting the negative findings from Expts 3 and 4.

reactions of interest to novel events, constitutes part of the core of the mature conception of objects, guiding humans' strongest intuitions about object persistence and change (Spelke, 1991). With development, identity judgements may come to be influenced by numerous additional factors, such as the smoothness of object motion, the constancy of object shape and colouring, and the kind of object under consideration (Wiggins, 1980; Xu & Carey, 1992). These developments extend human physical conceptions, but they may not alter the primary ways in which humans trace physical bodies through time.

Acknowledgements

Supported by grants to Elizabeth S. Spelke from NIH (HD-13248, HD23103) and NSF (BNS-8613390) and by an NSF Graduate Research Fellowship to Daniel J. Simons. We thank Hilary Schmidt, Janet Macomber and Suzanne Wurster for assistance, and Elliott Blass, Linda Hermer and Andy Meltzoff for comments and suggestions. Parts of Expt 1 were previously discussed in a review paper by Spelke & Kestenbaum (1986).

References

Baillargeon, R. (1986). Representing the existence and the location of hidden objects: Object permanence in 6- and 8-month-old infants. *Cognition*, **23**, 21–41.

Baillargeon, R. (1987). Object permanence in 3.5- and 4.5-month-old infants. *Developmental Psychology*, **23**, 655–664.

Baillargeon, R. (1993). The object concept revisited: New directions in the investigation of infant's physical knowledge. In C. E. Granrud (Ed.), *Visual Perception and Cognition in Infancy*. Carnegie-Mellon Symposia on Cognition, vol. 23. Hillsdale, NJ: Erlbaum.

Baillargeon, R. & DeVos, J. (1991). Object permanence in young infants: Further evidence. *Child Development*, **62**, 1227–1246.

Baillargeon, R. & Graber, M. (1987). Where's the rabbit? 5.5-month-old infants' representation of the height of a hidden object. *Cognitive Development*, **2**, 375–392.

Baillargeon, R., Graber, M., DeVos, J. & Black, J. C. (1990). Why do young infants fail to search for hidden objects? *Cognition*, **24**, 255–284.

Ball, W. A. (1973). The perception of causality in the infant. Paper presented at the Society for Research in Child Development, Philadelphia, PA, April.

Banks, M. S. & Salapatek, P. (1983). Infant visual perception. In M. M. Haith & J. J. Campos (Eds) & P. Mussen (Series Ed.), *Handbook of Child Psychology*, vol. 2, *Infancy and Developmental Psychobiology*. New York: Wiley.

Bower, T. G. R. (1982). *Development in Infancy*, 2nd ed. San Francisco: Freeman.

Bower, T. G. R., Broughton, J. M. & Moore, M. K. (1971). Development of the object concept as manifested in the tracking behavior of infants between 7 and 20 weeks of age. *Journal of Experimental Child Psychology*, **11**, 182–193.

Carey, S. (1991) Knowledge acquisition: Enrichment or conceptual change? In S. Carey & R. Gelman (Eds), *Epigenesis of Mind: Essays on Biology and Cognition*, pp. 1257–1291. Hillsdale, NJ: Erlbaum.

Carey, S., Klatt, L. & Schlaffer, M. (1992). Infants' representations of objects and nonsolid substances. Unpublished manuscript, MIT.

Cornell, E. H. (1979). The effects of cue reliability on infants' manual search. *Journal of Experimental Child Psychology*, **28**, 81–91.

Fischer, K. W. & Bidell, T. (1991). Constraining nativist inferences about cognitive capacities. In S. Carey & R. Gelman (Eds), *Epigenesis of Mind: Essays on Biology and Cognition*, pp. 199–235. Hillsdale, NJ: Erlbaum.

Fodor, J. A. (1983). *The Modularity of Mind*. Cambridge, MA: Bradford/MIT Press.

Geach, P. (1962). *Reference and Generality*. Ithaca, NY: Cornell University Press.

Gopnik, A. (1988). Conceptual and semantic development as theory change. *Mind and Language*, 3, 197–216.

Haith, M. M. (1993). Future-oriented processes in infancy: The case of visual expectations. In C. E. Granrud (Ed.), *Visual Perception and Cognition in Infancy*. Carnegie-Mellon Symposia on Cognition, vol. 23. Hillsdale, NJ: Erlbaum.

Harris, P. L. (1975). Development of search and object permanence during infancy. *Psychological Bulletin*, 82, 332–344.

Harris, P. L. (1987). The development of search. In P. Salapatek & L. B. Cohen (Eds), *Handbook of Infant Perception*. New York: Academic Press.

Hirsch, E. (1982). *The Concept of Identity*. Cambridge, MA: Harvard University Press.

Hume, D. (1962). In D. G. C. Macnabb, (Ed.), *Treatise of Human Nature. Book I: Of the Understanding*. New York: World Publishing Co.

Karmiloff-Smith, A. (1992). *Beyond Modularity*. Cambridge, MA: Bradford/MIT Press.

Kellman, P. J. (1993). Kinematic foundations of infant visual perception. In C. E. Granrud (Ed.), *Visual Perception and Cognition in Infancy*. Carnegie-Mellon Symposia on Cognition, vol. 23. Hillsdale, NJ: Erlbaum.

Kellman, P. J. & Spelke, E. S. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology*, 15, 483–524.

Leslie, A. (1988). The necessity of illusion: Perception and thought in infancy. In L. Weiskrantz (Ed.), *Thought without Language*. Oxford: Clarendon Press.

Leslie, A. (1991). Infants' understanding of invisible displacement. Paper presented at the Society for Research in Child Development, Seattle, WA, April.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds), *Mental Models*, pp. 299–324. Hillsdale, NJ: Erlbaum.

Michotte, A. (1963). *The Perception of Causality*. New York: Basic Books.

Moore, M. K., Borton, R. & Darby, B. L. (1978). Visual tracking in young infants: Evidence for object identity or object permanence? *Journal of Experimental Child Psychology*, 25, 183–198.

Moore, M. K. & Meltzoff, A. N. (1978). Imitation, object permanence and language development in infancy: Toward a neo-Piagetian perspective on communicative and cognitive development. In F. D. Minifie & L. L. Lloyd (Eds), *Communicative and Cognitive Abilities: Early Behavioral Assessment*. Baltimore: University Park Press.

Piaget, J. (1952). *The Origins of Intelligence in Children*. New York: International University Press.

Piaget, J. (1954). *The Construction of Reality in the Child*. New York: Basic Books.

Piaget, J. (1973). *The Psychology of Intelligence*. (M. Piercy & D. E. Berlyne, Trans.). Totowa, NJ: Littlefield, Adams. (Originally published in 1947.)

Piaget, J. (1976). *The Grasp of Consciousness*. Cambridge, MA: Harvard University Press.

Rosenthal, R. & Rosnow, R. L. (1991). *Essentials of Behavioral Research: Methods and Data Analysis*, 2nd ed. New York: McGraw-Hill.

Ross, G. S. (1980). Categorization in 1- to 2-year-olds. *Developmental Psychology*, 16, 391–396.

Rozin, P. (1976). The evolution of intelligence and access to the cognitive unconscious. In J. M. Sprague & A. Epstein (Eds), *Progress in Psychobiology and Physiological Psychology*, vol. 6. New York: Academic Press.

Slater, A., Morison, V. & Rose, D. (1984). Habituation in the newborn. *Infant Behavior and Development*, 7, 183–200.

Spelke, E. S. (1991). Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey & R. Gelman (Eds), *Epigenesis of Mind: Essays on Biology and Cognition*. Hillsdale, NJ: Erlbaum.

Spelke, E. S., Breinlinger, K., Macomber, J. & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, 99, 605–632.

Spelke, E. S., Katz, G., Purcell, S. E., Ehrlich, S. M. & Breinlinger, K. (1994). Early knowledge of object motion: Continuity and inertia. *Cognition*, 51, 131–176.

Spelke, E. S. & Kestenbaum, R. (1986). Les origines du concept d'objet. *Psychologie Française*, 31, 67–72.

Spelke, E. S., Simmons, A., Breinlinger, K., Jacobson, K. & Macomber, J. (1993). Developing knowledge of gravity. I: Infants' sensitivity to hidden object motion. Unpublished manuscript.

Tighe, T. J. & Leaton, R. N. (1976). *Habituation: Perspectives from Child Development, Animal Behavior, and Neurophysiology*. Hillsdale, NJ: Erlbaum.

von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, **30**, 369–382.

von Hofsten, C. (1983). Catching skills in infancy. *Journal of Experimental Psychology: Human Perception and Performance*, **9**, 75–85.

von Hofsten, C., Spelke, E. S., Vishton, P. & Feng, Q. (1993). Principles of predictive catching in 6-month-old infants. Paper presented at the meeting of the Psychonomic Society, Washington, DC, November.

Welford, A. T. (1968). *Fundamentals of Skill*. London: Methuen.

Wellman, H. M., Cross, D. & Bartsch, K. (1986). Infant search and object permanence: A meta-analysis of the A-Not-B error. *Monographs of the Society for Research in Child Development*, **51**, Serial No. 214.

Wiggins, D. (1980). *Sameness and Substance*. Cambridge, MA: Harvard University Press.

Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, **358**, 749–750.

Xu, F. & Carey, S. (1992). Infants' concept of numerical identity. Paper presented at the Boston University Language Acquisition Conference.

Received 7 April 1992; revised version received 25 January 1994

Appendix

In order to investigate whether adults' apprehension of object identity accords with the continuity and the smoothness principles, adult subjects were shown the occlusion events from Expts 1–4. They were asked to judge whether one or two objects participated in each event.

The 12 subjects (six males, six females) ranged in age from 19 to 27 years (mean age, 21 years). None had formal training in perception or development. They were presented in a latinized order with the continuous and discontinuous events from Expts 1 and 2, the constant speed event from Expt 3, and the constant speed, changed speed, and immediate reappearance events from Expt 4. Each event was

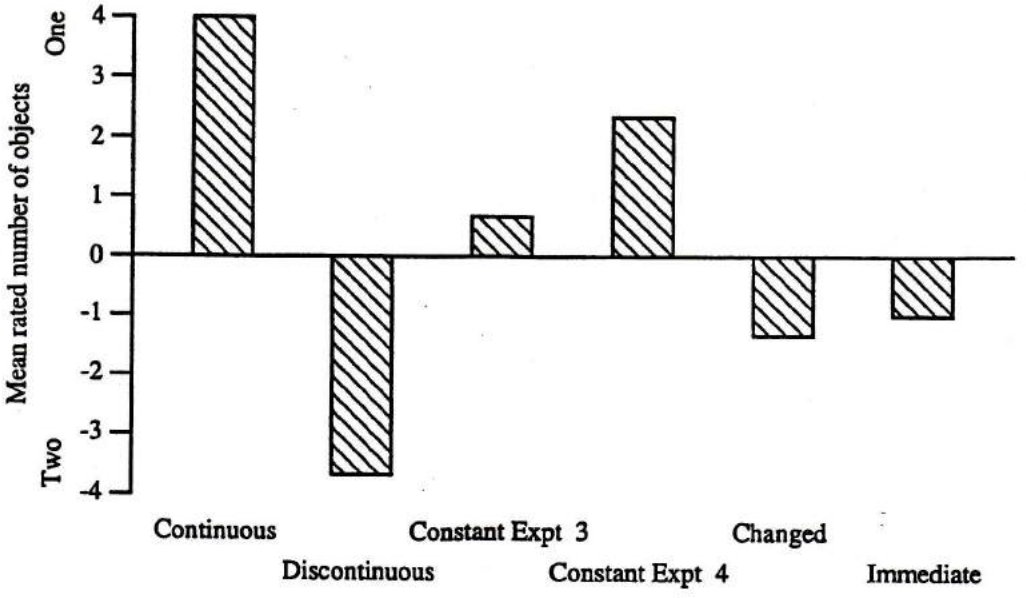

Figure 9. Adults' mean ratings of object identity vs. distinctness for each of the occlusion events of Expts 1–4.

presented continuously for 60 s in the apparatus used with infants, with the adult's head positioned to correspond to the infant's point of observation.

Before the events were presented, each subject was given instructions adapted from studies by Kellman & Spelke (1983). They were asked to give their impression about the number of objects participating in each event on a scale from −4 (strong impression of two objects) to 4 (strong impression of one object).

Figure 9 presents the mean ratings for each of the displays. Two-tailed t tests comparing the ratings for each display to the neutral point of 0 revealed highly significant tendencies to judge that the continuous event involved one object (SD = 0), and that the discontinuous event involved two objects ($t(11) = -44.08, p<.001, r = .997$). There was also a tendency to judge that the constant speed event from Expt 4 involved one object ($t(11) = 2.78, p<.02, r = .642$). Judgements for the other displays did not differ reliably from 0.

In order to compare adults' ratings of the different displays, the ratings were analysed by a one-way repeated-measures analysis of variance. This analysis revealed a significant effect of display ($F(5,55) = 13.02, p<.001$, eta = .542). Newman–Keuls tests indicated that the continuous event was judged to involve a single object significantly more strongly than the discontinuous event, the changed speed event, the immediate reappearance event (all $ps<.001$), or the constant speed event from Expt 3 ($p<.01$). In addition, the discontinuous event was judged to involve two objects significantly more strongly than either of the two constant speed events (both $ps<.001$), the changed speed event ($p<.05$), or the immediate reappearance event (<.05). Finally, the constant speed event from Expt 4 was judged to involve one object significantly more strongly than the changed speed event ($p<.01$) or the immediate reappearance event ($p<.05$).

These judgement patterns provide evidence that adults' perception of object identity is affected strongly and consistently by the apparent continuity or discontinuity of object motion. Adults' judgements also provided evidence that their perception of object identity is affected by the apparent constancy or change in the speed of object motion, but that this effect is neither as strong nor as consistent as the effect of continuity/discontinuity.