Research Article

ATTENTIVE TRACKING OF OBJECTS VERSUS SUBSTANCES

Kristy vanMarle and Brian J. Scholl

Yale University

Abstract—*Recent research in vision science, infant cognition, and word learning suggests a special role for the processing of discrete objects. But what counts as an object? Answers to this question often depend on contrasting object-based processing with the processing of spatial areas or unbound visual features. In infant cognition and word learning, though, another salient contrast has been between rigid cohesive objects and nonsolid substances. Whereas objects may move from one location to another, a nonsolid substance must pour from one location to another. In the study reported here, we explored whether attentive tracking processes are sensitive to dynamic information of this type. Using a multiple-object tracking task, we found that subjects could easily track four items in a display of eight identical unpredictably moving entities that moved as discrete objects from one location to another, but could not track similar entities that noncohesively "poured" from one location to another—even when the items in both conditions followed the same trajectories at the same speeds. Other conditions revealed that this inability to track multiple "substances" stemmed not from violations of rigidity or cohesiveness per se, because subjects were able to track multiple noncohesive collections and multiple nonrigid deforming objects. Rather, the impairment was due to the dynamic extension and contraction during the substancelike motion, which rendered the location of the entity ambiguous. These results demonstrate a convergence between processes of midlevel adult vision and infant cognition, and in general help to clarify what can count as a persisting dynamic object of attention.*

One of the most important questions that can be asked about any process is the nature of the units over which that process operates. For many cognitive and perceptual processes, these underlying units turn out to be representations of discrete *objects*. Prioritized processing of objects has been observed in recent research in many areas of cognitive science, including vision science, infant cognition, word learning, and higher-level cognition (for respective reviews, see Scholl, 2001; Carey & Xu, 2001; Bloom, 2000, chap. 4; and Prasada, Ferenz, & Haskell, 2002). But what counts as an object? A popular strategy for addressing this question across many of these domains has been to contrast object-based processing with processing of other types of units, such as unsegmented spatial areas or unbound visual features. In the study of infant cognition and word learning, however, another salient contrast has been between objects and nonsolid *substances*.

The distinction between objects and substances dates back at least to Aristotle, who claimed that the essence of an entity is a combination of both the *matter* of which the entity is made and the *form* of the entity (Prasada, 1999). Thus, objects, which have both matter and form, were differentiated from substances, which are themselves matter but have no inherent form.[1] This distinction is also evident in most human languages in that different syntax and morphology is used to refer to objects (as count nouns) and substances (as mass nouns): For example, one says, "three books" but not "some book," and "some sand" but not "three sands." Young children demonstrate knowledge of this distinction even before they produce such forms, and the eventual use of this distinction to infer the appropriate referent of a label only reinforces this distinction (e.g., Soja, 1992; Soja, Carey, & Spelke, 1991; see also Hall, 1996).

Objects and substances have also been contrasted with respect to the types of entities that young infants are able to track and quantify. Suppose an infant is shown a puppet stage containing one object, and the stage is then partially covered by a screen, which occludes the object. A second object is then visibly added behind the screen by the experimenter, and finally the screen is removed. Many studies have demonstrated that infants as young as 5 months will look longer when the screen drops to reveal only a single object, which is an "impossible" outcome, than when two objects are revealed (e.g., Chiang & Wynn, 2000; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992). Apparently, the infants have tracked the objects and quantified the displays, and expect there to be two objects when the screen is removed—and thus look longer when this expectation is violated. (Similar effects are observed for other violations, such as when a screen occludes two objects, one of the objects is taken out of the display, and the screen is removed to reveal two objects, rather than one.) Chiang and Wynn (2000) showed that 8-month-old infants succeed on this type of task—that is, they look longer at the anomalous outcomes—when the items are rigid cohesive objects, but fail in some circumstances when each "item" to be quantified is a collection of multiple elements that are moved together. (Success is observed only when the transformation from separate elements into a single collection is made salient in various ways.) This failure to track and quantify collections could be due either to the collections' violation of cohesion (in that they consist of multiple bounded elements) or to their violation of rigidity (in that the individual elements can undergo relative motion).

Recently, Huntley-Fenner, Carey, and Solimando (2002) addressed the object-substance distinction in infancy more directly. They showed that 8-month-old infants succeed on this type of task (i.e., look longer at the anomalous outcome) when the items are rigid cohesive objects, but fail in the identical procedure when the items are piles of sand that are poured behind the screen. The rigid cohesive objects used in this study were shaped like sand piles and coated with sand, making the

1. We can further distinguish between nonsolid substances (like sand or water) and solid substances (like wood or metal). In this article, we consistently use the term "substance" to refer only to nonsolid substances. In this usage, we follow the focus of recent work in infant cognition (e.g., Huntley-Fenner, Carey, & Solimando, 2002), rather than work on higher-level cognition (e.g., Prasada et al., 2002), which typically follows Aristotle's use of "matter" to encompass both solids and nonsolids.

Address correspondence to Brian J. Scholl, Department of Psychology, Yale University, Box 208205, New Haven, CT 06520-8205; e-mail: brian.scholl@yale.edu.

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two kinds of items perceptually similar when at rest. Infants also succeeded in a condition in which the behavior of the items violated rigidity, but not cohesion, leading these authors to conclude that infants' failure with substances (and with Chiang & Wynn's, 2000, collections) is due to the violation of cohesion per se. On the basis of these studies, Huntley-Fenner et al. concluded that even young infants appear to differentiate between objects and substances.

Another domain in which discrete objects are often critical units of processing is adult attention, which has spawned a large literature on *object-based attention* (see Scholl, 2001, for a review). In this literature, objects are frequently contrasted with both spatial areas and unbound visual features. For example, attention often selects particular target objects but not other objects that may spatially overlap the targets (e.g., Duncan, 1984; Most et al., 2001; O'Craven, Downing, & Kanwisher, 1999; Pylyshyn & Storm, 1988), and attending to one feature of an object may entail attending to other features of that object (e.g., Duncan & Nimmo-Smith, 1996; O'Craven et al., 1999). No previous studies of visual attention, however, have contrasted objects with substances, perhaps for an obvious reason: Surely the visual system itself does not "know" about the object-substance distinction! Still, objects and substances typically behave in very different and characteristic ways: An object moving from A to B constitutes a very different kind of shifting visual array than a substance that pours from A to B. Accordingly, our goal in this study was to explore whether attentive tracking mechanisms are sensitive to such distinctions.

Another, more specific reason for pursuing this question lies in the relation of adults' object-based attention to object cognition in infancy. These two fields have traditionally developed independently, even while addressing many of the same questions. Recently, however, several researchers have suggested that these two fields may in fact be exploring the same underlying object-based processes (e.g., Carey & Xu, 2001; Scholl & Leslie, 1999; Wynn & Chiang, 1998). It therefore becomes important to determine whether mechanisms of object-based attention in adults are sensitive in some way to the differing behavior of objects and substances, because the results of Huntley-Fenner et al. (2002) demonstrate that infants do in some way draw this distinction.

In Experiment 1, we explored adults' ability to attentionally track multiple items that move either as objects or as substances (following the same trajectories at the same speeds in the two cases). In Experiment 2, we followed up this initial contrast with several other conditions designed to determine the critical difference between objectlike movement and substancelike movement. To our knowledge, this is the first study of this distinction in the context of adult visual attention. More generally, these experiments help to clarify what can count as a persisting dynamic object of attention.

EXPERIMENT 1A: TRACKING OBJECTS VERSUS SUBSTANCES

Exploring the nature of attended objects can be a tricky business, because with enough time and effort, observers are able to treat almost anything as an object (Marr, 1982). Accordingly, most researchers have attempted to get at the visual system's "default" characterization of objects by limiting processing in some way—for example, by using strict temporal limitations (as in typical spatial-cuing or divided-attention studies; e.g., Duncan, 1984; Egly, Driver, & Rafal, 1994) or by imposing a high attentional load (as in multiple-object tracking studies; e.g., Pylyshyn & Storm, 1988). Here we investigated object tracking under a difficult attentional load, using the multiple-object tracking (MOT) task (Pylyshyn & Storm, 1988). In this task, subjects initially see eight identical items. Four of these then blink, which indicates their status as targets, and then all of the (again identical) items begin moving independently and unpredictably about the screen. When their motion stops, subjects must indicate which of the eight items are the four original targets.

Many previous studies have confirmed that subjects can succeed at this task when the items move as rigid cohesive objects (e.g., Scholl & Pylyshyn, 1999; Scholl, Pylyshyn, & Feldman, 2001). In this experiment, we contrasted a condition with this type of motion with a condition in which the items followed the same trajectories at the same speeds, but moved in a nonrigid and noncohesive manner—essentially "pouring" from one location to another, in the manner of nonsolid substances. (Because the effects obtained are perceptually salient, we encourage readers to view demonstrations of our actual displays on the Web, at http://www.yale.edu/perception/substances/.)

Method

Participants

Twenty naive Yale University undergraduates (10 in each of two conditions) participated in an individual session either to fulfill an introductory psychology course requirement or for monetary payment. All subjects had normal or corrected-to-normal acuity.

Apparatus

The tracking animations were presented on the built-in display of an iMac computer. Observers were positioned approximately 38 cm from the monitor, without head restraint, so that the display subtended approximately 44° by 33° of visual angle. Eye movements were not monitored, and no special instructions were given concerning fixation, because different fixation conditions have been found not to affect performance on the MOT task. Animations were constructed (as described in the next paragraph) using the Infini-D animation software, and were presented to subjects using the MacStim platform (Darby, 2002). All animations involved perceptually smooth motion (i.e., non-apparent motion).

Stimuli and procedure

Each trial employed four target items and four distractor items, all initially presented as identical white squares (subtending 1.73°) on a black background. Each item's initial position, final position, and four intermediate landmark positions were determined by random selection from an invisible 10×8 matrix, with the constraint that no two adjacent squares could simultaneously contain objects. Each item moved linearly from position to position in this manner, with haphazard timing resulting in staggered motion (such that different items did not reach their intermediate landmark positions at the same time). (These motions resulted in sequences of 3- to 4-s asynchronous "bursts" of motion, rather than the fully continuous motion used in most earlier MOT studies.) An 18-s animation of this type was created for each trial; the trajectory for each item was independent and unpredictable. At the beginning of each trial, four randomly selected items blinked several times to indicate their status as targets. Subjects then had to attentionally track these four items throughout the motion sequence, and use the computer mouse to indicate the four targets after the motion had ceased.

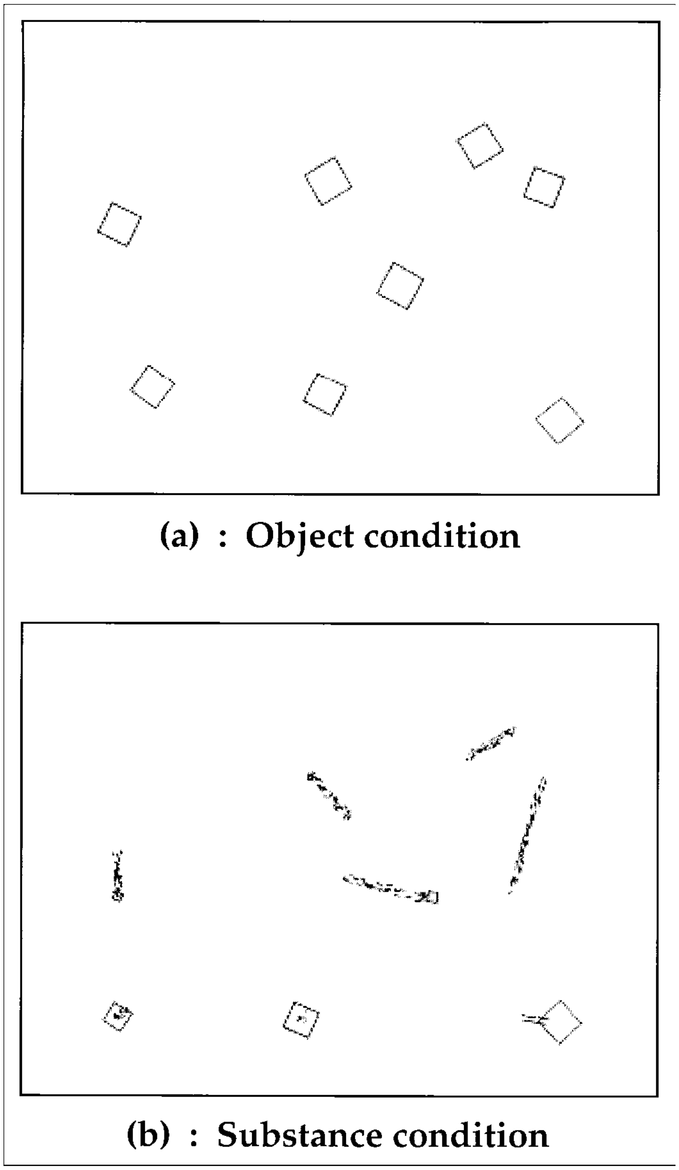

Fig. 1. Sample midtrial screen shots for the object (a) and substance (b) conditions. Actual displays were white on black. See the text for details, and http://www.yale.edu/perception/substances/ for dynamic demonstrations.

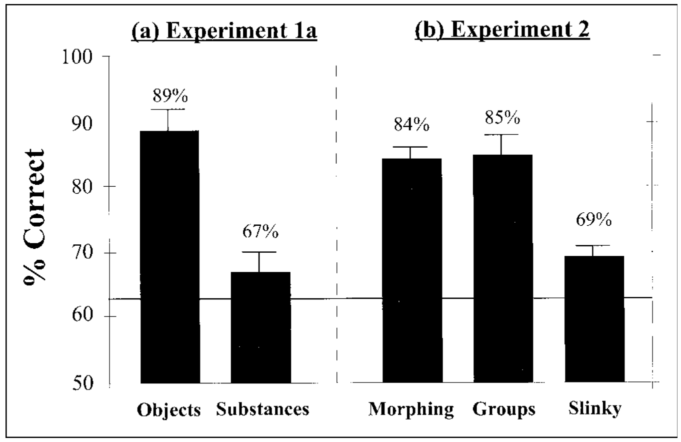

Fig. 2. Mean tracking accuracy and standard error for each condition of Experiment 1a (a) and Experiment 2 (b). The horizontal line running through the graph represents chance performance with multiple-object tracking, considered as the performance obtained by focally tracking only one object and guessing on the others—62.5% when tracking four items in a display of eight.

Conditions and design

Two types of motions were presented. The *object* condition was similar to previous MOT displays: Each square simply translated across the screen during its motion (at approximately 5.48°/s), maintaining its rigid boundaries. In the *substance* condition, each square moved from position to position by progressively disintegrating into many small pixels, which "poured" as a stream of many small individual elements to the next landmark position. These substancelike streams were approximately 0.65° wide and up to 12.8° long. Because the landmarks were often far apart, a stream typically "grew" from its trailing end out of its initial position, expanded to its maximum length (over the course of 1 s), then moved until the stream's leading edge reached the new position, at which point the stream reconstituted into a square at its new location (see the on-line movies for examples). Critically, these transformations were temporally locked to the motion in the object condition, such that the motions in the two cases followed identical trajectories at the same speeds. These two conditions were tested between subjects; for each condition, 10 subjects completed 20 randomly ordered trials, following 3 practice trials. A sample midtrial screen shot of each condition is depicted in Figure 1.

Results and Discussion

Tracking accuracy was recorded on each trial. Because there were always four targets, accuracy on a given trial was always 0, 25, 50, 75, or 100%. The mean percentage correct for each condition is shown in Figure 2a. Overall, tracking accuracy was high (and comparable to that observed in previous MOT studies) in the object condition, at 89%. In contrast, tracking in the substance condition was near chance, at 67% (chance in MOT is calculated as the accuracy obtained from tracking only a single item and guessing on the rest—62.5% in this case; see the appendix of Scholl et al., 2001).

This difference—both massive (22%) and statistically significant, $t(18) = 4.822$, $p < .001$—confirms that multiple *object* tracking is aptly named, as regards the contrast between objects and substances. (All statistical tests reported in this article used two-tailed comparisons.) At least one type of intuitively substancelike motion, wherein objects pour from one location to another, appears to frustrate the attentional mechanisms that mediate multielement attentive tracking.[2]

2. We note in passing that tracking in these two conditions feels quite different phenomenologically, as perhaps can be experienced in the on-line demonstrations. What success is possible in the substance condition seems to be mediated by a constantly updating prediction of where an item should be next, rather than by continuous tracking, as in the object condition. Several subjects spontaneously noted this difference in their postexperimental debriefing.

EXPERIMENT 1B: NONOVERLAPPING OBJECTS VERSUS SUBSTANCES

Experiment 1a demonstrates that entities moving in a manner characteristic of nonsolid substances cannot be readily tracked by visual attention in the same way that discrete objects can. What characteristics of substancelike motion are responsible for this impairment? In Experiment 2, we explored the possible roles of rigidity, cohesion, and dynamic extension and contraction. Before considering such properties, however, we wanted to rule out a less theoretically interesting possibility: Because the substances in Experiment 1a frequently subtended a much greater extent than the objects, while moving through the same trajectories, they also tended to overlap more frequently and for a longer duration. Could such greater overlap ("crossing streams") impair tracking? On the one hand, greater overlap might be seen as an intrinsic aspect of substancelike motion in displays with multiple items. On the other hand, it is not obvious that this should impair substances more than objects: Though the substance condition involved more frequent and salient overlaps with the crossing streams, it was actually the objects that tended to exhibit greater proportional overlap, which could have resulted in segmentation difficulties.

To explore these issues, we replicated Experiment 1a using a new group of 20 observers (10 per condition), changing only the nature of the trajectories, so that the streams in the substance condition never overlapped during their motion. (Of course, we then used these same new trajectories for the object condition as well.) Under these conditions—also viewable on the Web site listed earlier—subjects were still much more accurate in the object condition than in the substance condition (96.1% vs. 83.5%, respectively), $t(18) = 3.804$, $p < .005$. The lack of overlapping entities did in fact improve performance, but it did so for both objects (89% in Experiment 1a vs. 96.1% in Experiment 1b), $t(18) = 2.174$, $p < .05$, and substances (67% vs. 83.5%), $t(18) = 3.775$, $p < .01$. The fact that substances were still impaired relative to objects in this experiment implies that the amount of overlap cannot fully account for the difference between conditions found in Experiment 1a.

EXPERIMENT 2: RIGIDITY VERSUS COHESION VERSUS EXTENSION

In Experiment 1, we observed an ability to attentionally track multiple objects, but an inability to attentionally track multiple substances. At least three theoretically salient factors might be responsible for this effect, all relating to constraints on objecthood that are violated in the substancelike motion.

Rigidity: The Morphing Condition

Whereas the items in the object condition of Experiment 1 always maintained their shapes as squares, the boundaries of the items in the substance condition were decidedly nonrigid, frequently shrinking, growing, disappearing, and reconstituting. These violations of rigidity may have signaled to the visual system that the items were not in fact persisting objects. To test this possibility, we employed a *morphing* condition, wherein the objects still moved as coherent entities (through the same trajectories as in Experiment 1a), but while doing so constantly "morphed" between different shapes (a circle, square, vertical or horizontal ellipse, or hexagon), constantly shifting their local boundaries (see Fig. 3a). Each item morphed into a new shape once per positional landmark, and thus five times per trial. The overall spatial extent of each item remained roughly identical throughout these transformations.

Cohesion: The Groups Condition

Whereas each item in the object condition (and in the morphing condition) always maintained a single unbroken boundary, each item in the substance condition frequently separated into many separate image elements, which later reconstituted into a uniformly bounded square. These violations of cohesion may have signaled to the visual system that each item was in fact a group of multiple independent objects, causing a difficulty in tracking the group as an individual. (A lack of cohesion is ultimately what Chiang & Wynn, 2000, and Huntley-Fenner et al., 2002, appealed to in order to explain why infants do not track and quantify piles of sand or collections of multiple entities; cf. Wynn, Bloom, & Chiang, 2002). To test this possibility, we employed a *groups* condition, wherein each object moved from position to position as a group of four small squares that underwent some relative motion while moving, but always moved as a local image cluster—intuitively, a group of items moving together, like a compact swarm of insects (see Fig. 3b). Each group initially formed from a single square, and then later reconstituted into a single square at the end of the trial. Thus, in addition to testing the ability to track groups of multiple independent entities, this condition touches on the transformation from objects to groups, and back. However, we focus here on the ability to track groups; other experiments to be reported elsewhere focus in more detail on objects that split and merge.

Extension: The Slinky Condition

Whereas each item in the object condition (and the morphing and groups conditions) always moved as a local image cluster, the items in the substance condition repeatedly moved in a particular type of nonrigid motion: extending from a local image area to a long extended feature cluster, then shrinking back into a local object. This peculiar type of nonrigid motion may have been a primary culprit in disrupting tracking. To see why, consider how you would track such a stimulus with your finger. You would track a small discrete object by simply continuously pointing at it. But how would you use your finger to track a long, slithering snake? Would you point at its head? Its middle? (What if its middle kept changing locations, as the snake stretched and shrunk?) This difficulty in determining *where* an extended object (and, in particular, an extended object whose boundaries are constantly shifting) is may seriously impair tracking in an attentionally demanding situation, because there is no single stable point for attention to bind to. To test this possibility, we employed a *Slinky* condition,[3] wherein the objects extended and contracted from position to position in the same manner as in the substance condition, but in doing so always kept a single unbroken boundary. This condition thus appeared to involve repeatedly expanding and contracting rectangles (see Fig. 3c).

3. Here we are using "Slinky" as a proper name. To those readers unfamiliar with this once-common children's toy, we offer our apologies and sympathy.

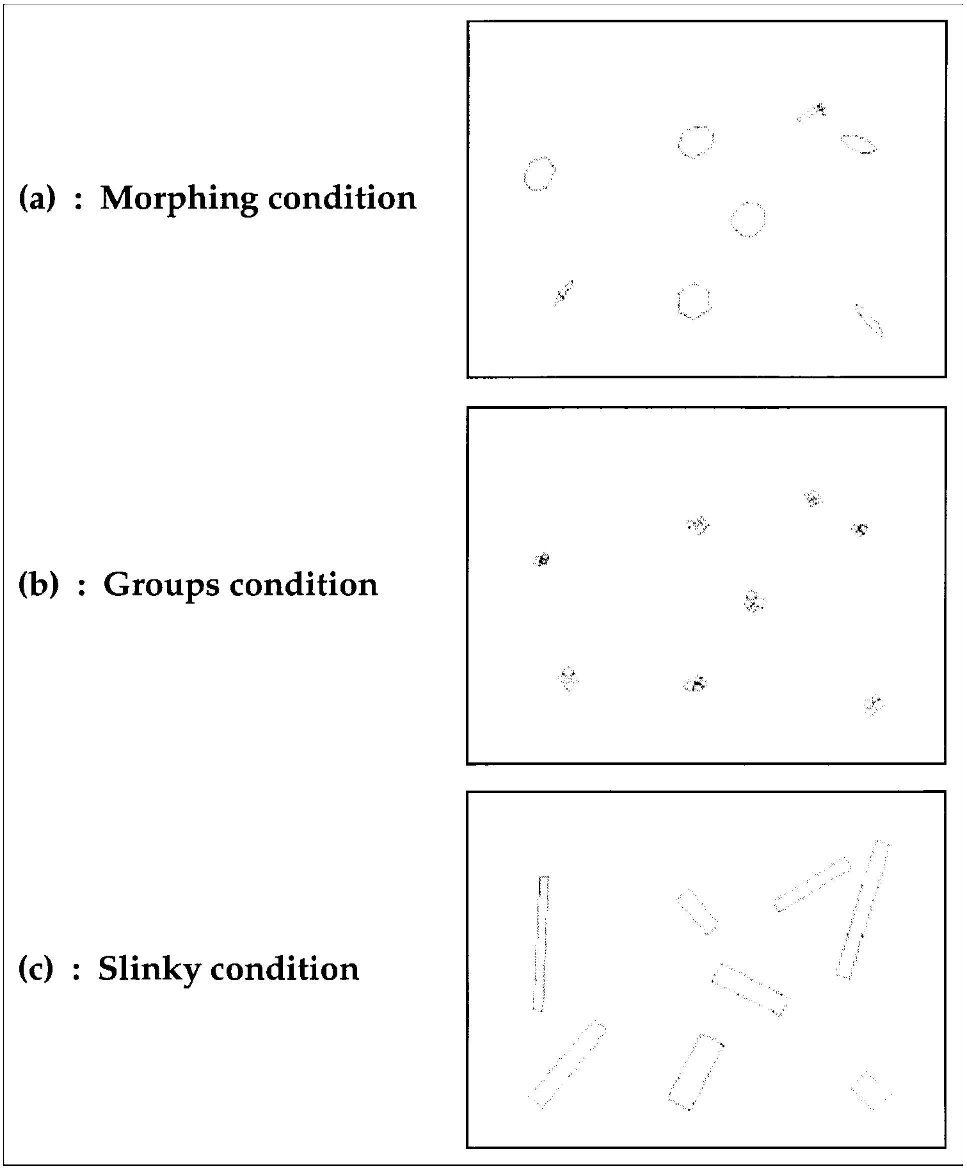

Fig. 3. Sample midtrial screen shots for the morphing (a), groups (b), and Slinky (c) conditions. Actual displays were white on black. See the text for details, and http://www.yale.edu/perception/substances/ for dynamic demonstrations.

Method

This experiment was identical to Experiment 1a, except that three new between-subjects conditions were used, as described. In particular, all of the items still moved through the same trajectories (and at the same speeds, etc.) as in Experiment 1a. Thirty new naive observers participated, 10 in each condition.

Results and Discussion

Tracking accuracy was recorded on each trial. The mean percentage correct for each condition is shown in Figure 2b. Inspection of this graph suggests that compared with the baseline object condition of Experiment 1a, the morphing and groups conditions showed no impairment, but subjects were significantly worse in the Slinky condition. These impressions were borne out by statistical analyses. A one-way omnibus analysis of variance, taking into account all five conditions across Experiments 1a and 2 (i.e., those conditions that all employed the identical trajectories), revealed that the conditions differed significantly, $F(4, 45) = 13.583$, $p < .001$. Planned comparisons revealed that performance in the Slinky condition (69%) was significantly worse than performance in the baseline object condition (89%), $t(18) = 5.45$, $p < .001$, but performance in the morphing and groups conditions (84% and 85%, respectively) was not, $t(18) = 1.175$, $p = .255$, and $t(18) = 0.840$, $p = .412$, respectively. Further planned comparisons revealed that performance in the morphing and groups conditions was significantly better than performance in the substance condition, $t(18) = 4.794$, $p < .001$, and $t(18) = 4.053$, $p < .001$, respectively, but performance in the Slinky condition was not, $t(18) = 0.0543$, $p = .594$. Finally, performance in the Slinky condition was significantly worse than performance in both the morphing and groups conditions, $t(18) = 6.315$, $p < .001$, and $t(18) = 4.54$, $p < .001$, which did not themselves differ, $t(18) = 0.168$, $p = .868$.

These results shed some light on the reasons for failure in the original substance condition of Experiment 1. Although the substance condition violated several intuitive constraints on objecthood, the culprit turned out to be neither rigidity per se (because of success in the nonrigid morphing condition) nor cohesion per se (because of success in the noncohesive groups condition). Rather, the critical factor that rendered attention unable to track substancelike movement in Experiment 1 appears to have been the extreme extension and contraction of the items' boundaries as they moved.

GENERAL DISCUSSION

The central result of this study was a salient inability to track multiple "substances"—that is, items that moved in a characteristically substancelike way, pouring from one location to another. This impairment was observed along with successful performance with standard rigid cohesive objects, even when the items in each condition followed the same trajectories at the same speeds. The additional morphing, groups, and Slinky conditions further refine this picture, suggesting that the impairment for substances is due not to their violations of rigidity or cohesion per se, but to their characteristic extension and contraction when moving—essentially making "the" location of the object ambiguous. (This explanation is entirely consistent with that given by Chiang & Wynn, 2000, who noted that one similarly cannot point to a single location occupied by a dispersed group of elements.) In at least this way, then, even mechanisms of visual attention are indirectly sensitive to the distinction between objects and substances.

The object-substance distinction has played a much greater role in developmental research and in higher-level cognition than in vision science. Indeed, some previous discussions have explicitly denied that theories of attention could have anything to say about this distinction. Prasada et al. (2002), for example, wrote in the context of their work on how people conceptualize objects versus substances: "Research on the representation and tracking of perceptual objects . . . does not address this question. . . . The mechanism involved in the tracking of perceptual objects is generally considered to be indexical in nature and thus is not sensitive to whether the entity being tracked is conceived of as an object or as some stuff" (p. 143). Although we certainly agree that perception is not sensitive to the *conception* of an entity as an object or substance, we disagree with the spirit of this sentiment. In our experiments, we have observed that perceptual tracking processes are sensitive to precisely this distinction—although this sensitivity is mediated not by a conception, but indirectly via differences in the dynamic *behaviors* of objects versus substances. Objects and substances may be conceived of differently (Prasada et al., 2002), but they also behave differently, in ways that have direct perceptual consequences. Thus, it remains possible that perceptual mechanisms may form the core of such distinctions, out of which later conceptual differences are eventually developed.

Such perceptual distinctions may also form the core of the infant's object-substance distinction. In this context, our results can be seen as yet another convergence between processes in infant cognition and adults' object-tracking processes (see Carey & Xu, 2001; Scholl, 2001, section 7.2; Scholl & Leslie, 1999; Wynn & Chiang, 1998). The ability of infants to track and quantify multiple entities depends critically on the nature of those entities: In some conditions, 8-month-olds are able to track and quantify rigid cohesive objects, but not collections of multiple entities—a result that could be due to the collections' violations of either cohesion or rigidity (Chiang & Wynn, 2000). Later studies looking directly at the object-substance distinction suggest that the critical factor is in fact cohesiveness per se, because infants can succeed with nonrigid but cohesive entities (Huntley-Fenner et al., 2002). On the basis of our contrast between the substance and groups conditions, in contrast, we concluded that the failure with substances was due to the characteristic extension and contraction, which essentially rendered the location of the entity ambiguous. Because Huntley-Fenner et al. (2002) did not test this possibility, we suspect that this type of dynamic extension and contraction—rather than the violation of cohesion per se—may also have been the culprit in their experiments. This prediction is an example of how research projects exploring adults' object-based attention and studies of the infant's object concept may usefully inform each other. In general, this study highlights ways in which these two literatures are exploring some of the same questions, and perhaps the same underlying mechanisms.

Beyond these links to other research areas, these results contribute directly to the study of what counts as an object of dynamic object-based attention. Previous studies of object-based attention have focused on contrasts with spatial areas or unbound visual features. Our results represent a new third contrast: Attentional tracking is primarily based on discrete objects, rather than locations or features—or substances. Future studies may now explore in more detail how attention is used to select and track deformable extended entities.

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