

## FAST-TRACK REPORT

# Interrupting infants' persisting object representations: an object-based limit?

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### Abstract

*Making sense of the visual world requires keeping track of objects as the same persisting individuals over time and occlusion. Here we implement a new paradigm using 10-month-old infants to explore the processes and representations that support this ability in two ways. First, we demonstrate that persisting object representations can be maintained over brief interruptions from additional independent events – just as a memory of a traffic scene may be maintained through a brief glance in the rearview mirror. Second, we demonstrate that this ability is nevertheless subject to an object-based limit: if an interrupting event involves enough objects (carefully controlling for overall salience), then it will impair the maintenance of other persisting object representations even though it is an independent event. These experiments demonstrate how object representations can be studied via their 'interruptibility', and the results are consistent with the idea that infants' persisting object representations are constructed and maintained by capacity-limited mid-level 'object-files'.*

### Introduction

Coherent visual experience depends not only on our ability to bind individual visual features into discrete object representations, but also on our ability to bind multiple views of objects over time and motion into the same *persisting* object representations. This is a major challenge for visual perception, since we frequently lose contact with objects from moment to moment – e.g. when we blink, or shift our gaze around a scene, or when one object occludes another. In this paper we describe and explore a new type of constraint based on the 'interruptibility' of persisting object representations in infancy.

### Object persistence in infancy

The nature of persisting object representations has been a salient theme across several recent research areas in the cognitive sciences. Two research areas in which such processing has been especially well characterized are in adult vision science and infant cognition. These two lines of research have converged on a consistent set of principles (see Spelke, 1998, 2000). To be seen as persisting

individuals, objects must: (1) trace spatiotemporally continuous paths through space and time (Aguiar & Baillargeon, 1999, 2002; Bremner, Johnson, Slater, Mason, Foster, Cheshire & Spring, 2005; Flombaum, Kunder, Santos & Scholl, 2004; Flombaum & Scholl, in press; Michotte, Thinès & Crabbé, 1964/1991; Scholl & Pylyshyn, 1999; Spelke, Kestenbaum, Simons & Wein, 1995); (2) maintain rigid cohesive boundaries over time (Cheries, Mitroff, Wynn & Scholl, 2005; Chiang & Wynn, 2000; Huntley-Fenner, Carey & Solimando, 2002; Mitroff, Scholl & Wynn, 2004, under review; Spelke, 2000; vanMarle & Scholl, 2003); and (3) respect each other's solid boundaries (Mitroff, Scholl & Wynn, 2005; Baillargeon, Spelke & Wasserman, 1985; Santos, 2004; Spelke, Breinlinger, Macomber & Jacobson, 1992).

Many studies with human infants have explored object persistence in what is perhaps its simplest form: a display that is momentarily occluded. In a typical task (e.g. see variants in Bonatti, Frot, Zangl & Mehler, 2002; Feigenson, Carey & Spelke, 2002; Kaldy & Leslie, 2003; Tremoulet, Leslie & Hall, 2000; Wynn, 1992; Wynn & Chiang, 1998; Xu & Carey, 1996), infants witness an object enter onto an empty stage and become occluded by a screen. After a brief pause (and perhaps some additional manipulations) the screen is removed, revealing a

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display that may be identical or different in various ways (e.g. involving a new number of objects behind the screen). Infants' persisting representations of the initial display can be observed via longer looking time to the changed displays at test.

What are the factors that mediate infants' ability to maintain such representations? Some fairly straightforward variables are surely involved; e.g. there must clearly be some overall limits related to the spatial extent of the screens, the speeds of the manipulations, or the brute duration of occlusion (e.g. Bremner *et al.*, 2005; Scholl & Nevarez, 2002). An ongoing challenge, however, is to understand *why* such limits obtain, and to interpret them in terms of underlying cognitive processes and resources.

### Interrupting object representations

The majority of the studies cited above have revealed nuanced *intrinsic* constraints on how an object must behave for it to be successfully represented as the same enduring individual over time, but these studies only rarely address the *extrinsic* challenges of everyday vision. In particular, the dynamic and haphazard nature of real-world visual experience requires that object representations be maintained not only through various manipulations of those objects, but also to extrinsic *interruptions* from other objects and events that we might attend. Such interruptions are ubiquitous in everyday life – e.g. as we safely speed through traffic despite frequent glances to the rearview mirror (or the radio dial) – but have often been factored out in most experimental designs involving object persistence. Our goal here is to factor one particular kind of simple interruption back in to studies of infants' object persistence, in order to ask about the nature of the underlying processes and resources.

Some extrinsic interruptions, of course, will succeed in impairing performance for relatively uninteresting reasons, simply because of their magnitude. For example, we might expect infants' performance to be impaired by a loud-enough noise, a bright-enough flash, a severe-enough physical disruption, etc. In this report, however, we attempt to equate the brute salience of all interrupting events, and to focus instead on their higher-order structure.

We draw inspiration in this regard from studies investigating persisting representations in adults' mid-level vision, which have revealed two characteristic constraints. First, many of our mid-level visual representations are fundamentally object-based, such that the visual system automatically (and often even irresistibly)

carves up a visual scene into discrete objects, which then become the mandatory 'currency' for other visual and cognitive processes such as attention (e.g. Scholl, 2001). The 'object file' framework, for example (Kahneman & Treisman, 1984; Kahneman, Treisman & Gibbs, 1992), posits a level of representation in which objects are distinguished and tracked over time via mid-level short-term memory tokens, despite changes to their locations, low-level visual information (e.g. 'red', 'round'), and even higher-level semantic information (e.g. 'bird', 'plane'). This level of representation may even be mandatory in some cases: for example, you can successfully track *objects*, but you cannot track locations or features under high attentional loads (e.g. Scholl, Pylyshyn & Feldman, 2001); and objects serve as the underlying units of visual working memory in some cases (e.g. Vogel, Woodman & Luck, 2001; Xu & Chun, 2006).

A second constraint on such representations is that they are fueled by a capacity-limited resource, which seems to provide only approximately four object files which can operate in parallel (e.g. Cowan, 2001). As a result, only about four objects can be simultaneously tracked by attention (e.g. Pylyshyn & Storm, 1988), or be simultaneously encoded into visual working memory (e.g. Halberda, Simons & Wetherhold, under review; Luck & Vogel, 1997; cf. Alvarez & Cavanagh, 2004). There are several further varieties of evidence for a discrete limit of this sort (e.g. see Scholl & Xu, 2001), and its existence has also recently been observed and localized at the neural level in fMRI studies (Xu & Chun, 2006).

Though these constraints were initially discovered in the study of adults' mid-level vision, several investigators have recently found that these same underlying processes and constraints may also explain aspects of infants' object cognition (e.g. Carey & Xu, 2001; Chiang & Wynn, 2000; Scholl & Leslie, 1999). In particular, work with several different paradigms has now shown a similar capacity limit: infants are seemingly unable to represent more than three objects in parallel (Feigenson & Carey, 2003, in press; Feigenson, Carey & Hauser, 2002; Xu, Spelke & Goddard, 2005). Indeed, this has become a signature constraint of 'object-file' models of infant numerical processing. Both of these literatures, however, have yet to determine the limiting factors for maintaining these representations in our everyday visual environment that is replete with interruptions.

### The current study

The object-based and capacity-limited nature of adults' mid-level object representations fuels a specific prediction

about infants' object cognition. Deploying attention to an extrinsic interruption should impair infants' maintenance of a display, but only when both (1) the interruption and the initial display representation are processed via the same object-file system, and (2) the limits of this system are exceeded. Here we test this prediction in a comparison that isolates number *per se*, controlling for salience and overall visual extent. By testing infants' resilience to interruptions in this way, we aim to identify the resources that are used to maintain representations of persisting objects over time and occlusion as well as how they interact with other objects we might intermittently attend to in a scene more generally.

### Experiment 1: Surviving an extrinsic interruption

In this experiment 10-month-old infants simply had to maintain a representation of one or two dolls across a single interruption – an extrinsic event involving an independent object that occurred while the dolls were occluded. Infants' looking times to the display following the interruption were taken as a measure of the maintenance of their representation of the initial display of dolls. If this representation is maintained, then infants should look longer when the occluder was removed to reveal a new number of dolls than when it revealed the original number. In contrast, if the interruption destroys the initial representation, then there should be no difference at test based on the initial encounter.

Previous studies have indirectly tested whether infants' object memory is robust in the face of some types of interruptions. For example, studies investigating infants' numerical competence typically require that they attend to successive 'updates' of a display. Infants who have just witnessed an object disappear behind an occluder might be tested on whether they can track subsequent additions or subtractions to the same display (e.g. Feigenson *et al.*, 2002; Uller, Carey, Huntley-Fenner & Klatt, 1999; Wynn, 1992), or changes to the features of these objects (e.g. Kaldy & Leslie, 2005).

In all of these previous studies, however, the 'interruption' is typically an enduring addition to the display as well as another event of the same type that infants were already representing. In the present study, in contrast, the 'interruption' is not part of the primary display, but involves a completely independent object that simply traverses the space in front of the occluded display, and then exits the stage. Will infants still be able to maintain their initial representation of the dolls through this type of extrinsic interruption?

### Method

#### Participants

We tested 20 10-month-old infants (10 males, 10 females) from the greater New Haven area (range = 9 months, 29 days to 10 months, 27 days; mean = 10 months, 13 days). Five additional infants were tested but excluded from analysis due to fussiness (three) and experimenter error (two).

#### Apparatus

The stimuli were presented on a white foam-core stage measuring 50 cm high, 93 cm long and 34 cm deep. A small slot cut in the middle of the stage allowed for a yellow screen (30 cm by 18 cm) attached to a wooden dowel to be raised and lowered from below in order to occlude any objects on the stage. The experimenter could surreptitiously add or remove objects through an opening in the back wall of the stage (25 cm by 13.5 cm) that was concealed by a hinged trap door that was undetectable when closed. A shallow inset track spanned the length of the stage in front of the screen, on which interrupting objects could be placed and pulled across via strings. The entire stage area could be occluded by lowering a black fabric curtain attached to a rope behind the stage.

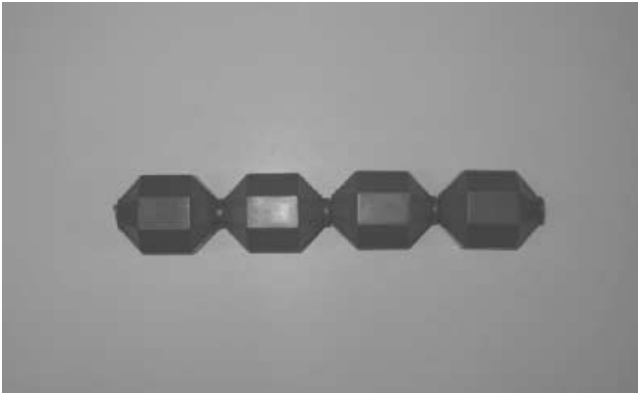
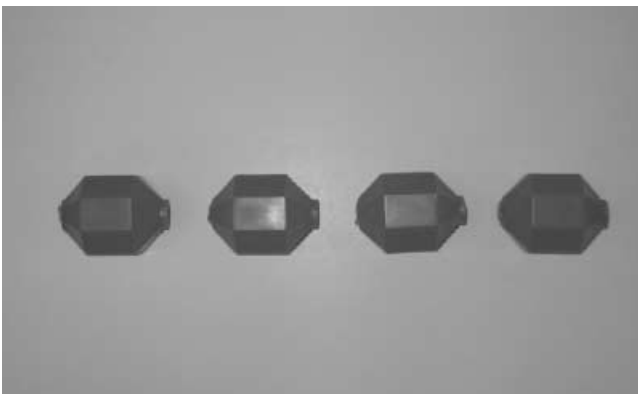
Participants sat in an infant seat approximately 1 meter from the front of the stage. Long black curtains to the left and right of the table blocked the infants' view of the rest of the room, which was dimly lit by a halogen lamp. A small camera mounted on top of the stage recorded the infants' responses, while on-line judgments of the infants' looking (recorded and controlled via 'X Hab' software; Pinto, 1996) could be made by peering through a small hole in the curtain directly adjacent to the stage.

#### Stimuli

The 'target' stimuli were two Mickey Mouse™ dolls (12 × 9 × 4 cm) which could squeak when squeezed. In addition, one of the two toys also had a small sleigh bell affixed to the back of its body. The 'interrupting' object was composed of four small plastic orange 'snap-lock' beads that were glued together into a single object (24 × 4 × 4 cm), as depicted in Figure 1a.

#### Procedure

Before entering the test room, infants were allowed to handle both Mickey Mouses™ and the interrupting

(a) **1-Object Interruption**(b) **2-Object Interruption**

**Figure 1** Close-up views of the interrupting object(s) used in (a) Experiment 1, and (b) Experiment 2.

object for one minute each. Immediately afterwards, the infant was brought into the testing room and seated in front of the stage. The parent was seated adjacent to the infants but faced away from the stage to prevent bias. During a brief introduction, the infants were familiarized to (a) the curtain (which punctuated the beginnings and ends of each trial) being raised and lowered three times; (b) the screen (which later occluded the toys) being raised and lowered three times; and (c) the interrupting object moving across the stage in front of the raised screen two times, with no other objects present. (Note that this event was perceptually identical to the retinal image involved in the actual interrupting event.)

Following this familiarization, infants were given two *Baseline* trials to measure their preference for looking at one versus two target objects (counterbalancing the order across subjects). The experimenter said 'Watch the screen!' as the screen was lowered to reveal either one or two of the dolls resting on the stage. An on-line observer

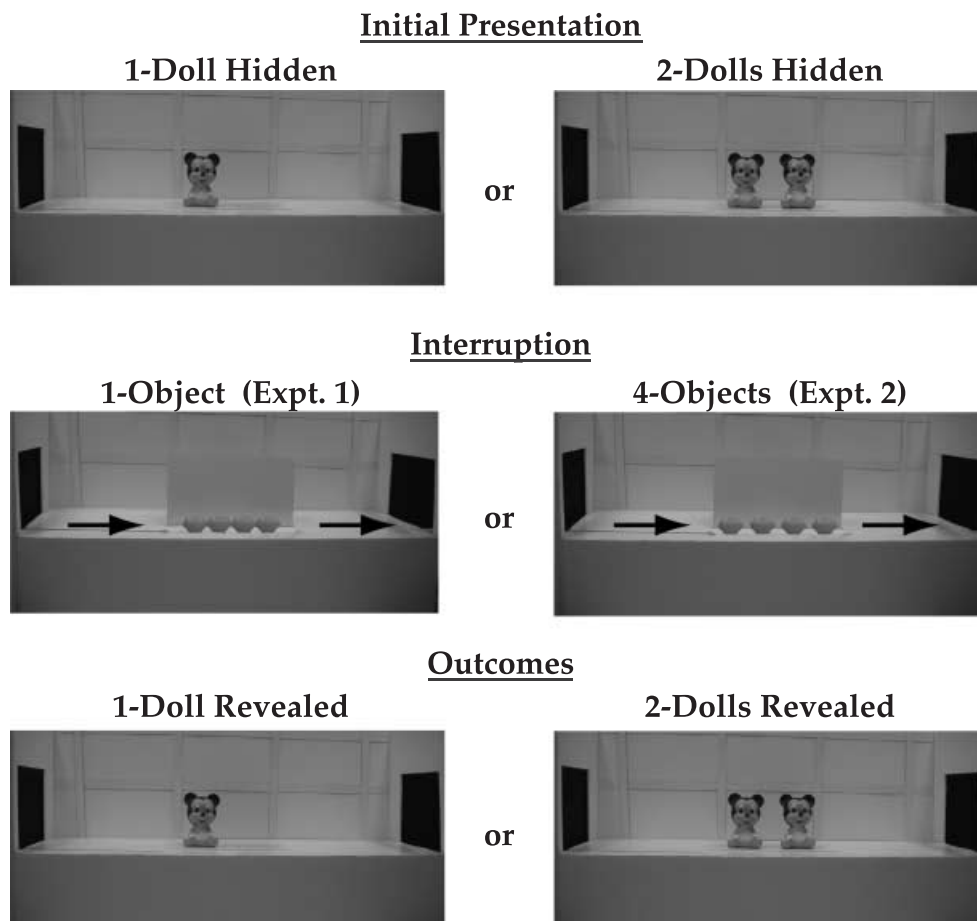
started recording an infant's looking time once the infant had attended to the stage area for at least .5 s. The trial ended and the curtain was dropped once the infant looked away from the stage area for 2 continuous s.

Infants were randomly assigned to either a *1-Doll-Hidden* or *2-Dolls-Hidden* test group, each of which contained six test trials that alternated between 'no change' and 'change' outcomes. Each trial began with the experimenter saying, 'Look [baby's name], look!' as their hand emerged from a small opening on the right with a doll. The experimenter squeaked the toy twice and placed it in the middle of the stage. In the *2-Dolls-Hidden* group infants again heard, 'Look [baby's name], look!' and the experimenter's hand re-emerged from the right with a second doll. The experimenter jingled the doll twice, then placed it alongside the first and retracted their hand from the stage. As the experimenter said 'Up goes the screen!', the screen was raised to occlude the doll(s) on the stage. The doll(s) remained occluded for 6 s, during which time the 'interruption' object glided across the stage (from left to right) on the track just in front of the screen (see Figure 2), taking the full 6 seconds from entry to exit. Once the interrupting object had exited the stage, the experimenter said 'Watch the screen!' and lowered the screen to reveal either one or two dolls. Infants' looking was recorded at this point in the same manner as in the *Baseline* trials.

### Results

Infants showed no preference during *Baseline* trials for 1 vs. 2 dolls (13.69 s vs. 11.23 s;  $t(1, 18) = 1.46, p = .16$ ). The looking times during the test phase, collapsed over test pairs, clearly indicate that the infants successfully maintained their representations of the number of toys behind the screen, despite the extrinsic interruption (see Figure 3).<sup>1</sup> Overall, 16 out of 20 infants exhibited longer looking at the 'change' outcomes ( $p = .01$ , two-tailed sign test). A 2 (familiarization group: 1 vs. 2)  $\times$  2 (test condition: 1 vs. 2) mixed-design ANOVA showed a significant interaction between Group (1 Doll vs. 2 Dolls hidden) and Outcome (1 Doll vs. 2 Dolls revealed,  $F(1, 18) = 4.76, p = .043$ ); infants looked significantly longer at the new number of dolls. No other main effects were significant.

<sup>1</sup> A large literature on infants' numerical competence has addressed whether or not infants' responses are based on number *per se*, or on properties that co-vary with number (e.g. area, contour length, density, etc.; Clearfield & Mix, 1999; Feigenson *et al.*, 2002; Feigenson, Dehaene & Spelke, 2004). However, the purpose of the current study was simply to demonstrate that those object properties infants represent (whatever they be) are able to survive brief interrupting events.



**Figure 2** Outline of the experimental design, distinguishing the nature of the interrupting events used in Experiment 1 (1 interrupting object), and Experiment 2 (4 interrupting objects).

### Discussion

Infants in this experiment were clearly able to maintain their representations of objects through not only the duration of occlusion, but also through the extrinsic interrupting event. Moreover, the particular structure of the interrupting object used here allows us to carefully manipulate the nature of the interruption in the next experiment – changing its physical structure in only a subtle way.

### Experiment 2: An object-based limit

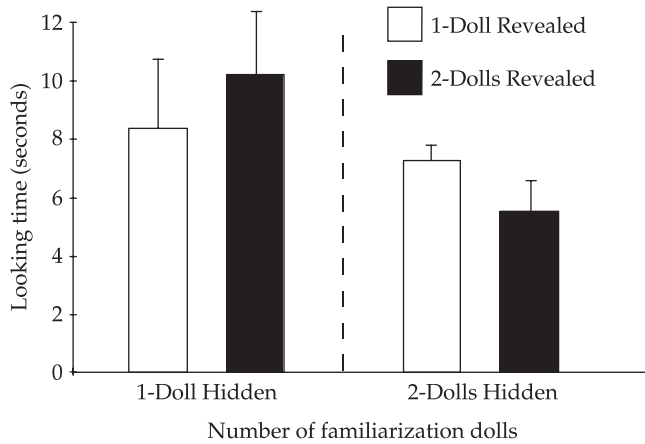
This experiment was identical to Experiment 1, except for one physically subtle but theoretically important change: the four ‘parts’ of the interrupting object in this experiment were now physically separated to produce four distinct objects (see Figure 1b). This resulting group

of four objects still traversed the display via common motion – indeed, the event was identical except for the small gaps between what had previously been the object parts. Critically, the interruption had all of the same visual features, including the same temporal duration. Based on the interpretation of infants’ object processing in terms of a capacity-limited object-file system, however, we predicted that this subtle change would require more than the available resources, and that this increased numerical load would thus foil the maintenance of the initial display’s representation.

### Method

#### Participants

We tested 20 10-month-old infants (9 males, 11 females) from the greater New Haven area (range = 9 months, 29 days to 10 months, 26 days; mean = 10 months, 14 days).



**Figure 3** Test-trial looking times for Experiment 1, collapsed across test pair. Error bars represent standard errors.

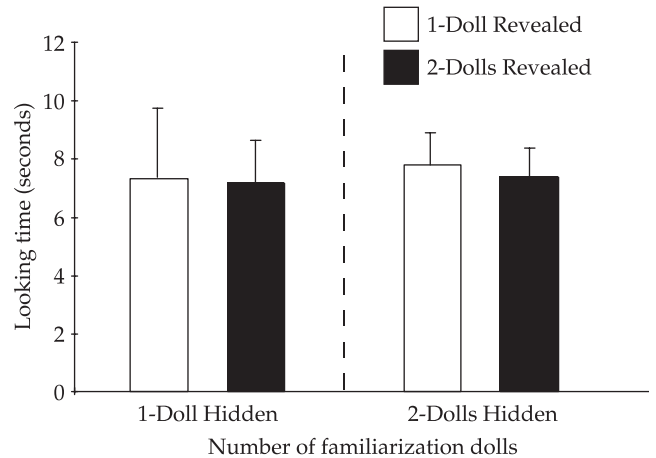
One additional infant was tested but excluded from analysis due to fussiness and experimenter error.

#### Stimuli and procedure

All aspects of the familiarization and experimental procedures were identical to Experiment 1, except as noted here. The interrupting objects that had previously been glued together were now separated into four distinct beads (each measuring 6 cm long, by 4 cm high, by 4 cm thick; see Figure 1b). Each object was separated by 2 cm of space, marginally increasing the display length in Experiment 2 to 30 centimeters, but not affecting the overall spatial extent of the interrupting stimulus itself. During the occlusion interval, these four objects were pulled across the stage, moving with common motion but always maintaining their relative separation (see Figure 2). The duration of this interruption was identical to that in Experiment 1.

#### Results

An initial test again demonstrated that infants showed no preference during Baseline trials for 1 vs. 2 toys (11.46 s vs. 12.62 s;  $t(1, 18) = .599, p = .56$ ). As depicted in Figure 4, the looking times which resulted from the test phase (collapsed over test pairs) clearly indicate that the four interrupting objects impaired the infants' ability to maintain their representations of the number of toys behind the screen. Overall, 12 out of 20 infants exhibited longer looking at the 'change' outcomes ( $p = .5$ , two-tailed sign test). When the looking times were submitted to a 2 (familiarization group: 1 vs. 2)  $\times$  2 (test condition: 1 vs. 2) mixed-design ANOVA, neither main effect was significant (familiarization group:  $F(1, 18) = .032, p = .86$ ;



**Figure 4** Test-trial looking times for Experiment 2, collapsed across test pair. Error bars represent standard errors.

test condition:  $F(1, 18) = .068, p = .80$ ). And, in contrast to Experiment 1, there was no reliable interaction between these two factors ( $F(1, 18) = .005, p = .94$ ), indicating that infants' looking times to the test displays did not differ based on their initial familiarization.<sup>2</sup>

#### Discussion

The results of this experiment indicate that not all interruptions are survivable, and moreover that at least some interruptions will impair persisting object representations based on their higher-level structure – here, based on the *number* of objects involved – controlling for overall salience.

#### General discussion

The current study yielded two primary results. First, infants' representations of persisting individuals through occlusion (maintained representations of 1 vs. 2 objects) survived an extrinsic interrupting event in which an independent object traversed the display during the occlusion period. Second, however, such persisting representations were destroyed when the very same interrupting event was presented in a subtly different way – as four distinct objects, controlling for overall duration, spatial extent and visual features.

<sup>2</sup> Collapsed across outcome types, infants who saw the 4-object interruption looked no longer on average than infants who saw the 1-object interruption (7.3 s vs. 7.8 s;  $t(39) = .411, p = .68$ ). Thus, the difference in infants' performance between Experiments 1 and 2 cannot be attributed to the 4-object interruption being more interesting or anomalous than the 1-object interruption.

Both of these results are theoretically interesting, in different ways. The finding that infants' representations can survive at least some extrinsic interruptions is consistent with previous demonstrations that such representations are also maintained through various other types of display manipulations, such as the addition or subtraction of additional objects from the display between the initial and final encounters (e.g. Feigenson *et al.*, 2002; Feigenson & Carey, 2003, in press; Kaldy & Leslie, 2005; Wynn, 1992). Critically, however, these previous manipulations often involved the same types of events as those being maintained from the initial familiarization display (or they interacted with the original display in meaningful ways). In addition, these other objects were then present in the displays for the remainder of the trial. As a result of both of these factors, such additional manipulations may have been survivable because they were not experienced as extrinsic *interruptions* at all; rather, they may simply have been encoded as intrinsic parts of the (single) event being processed and maintained. Neither of these factors was true in the present study: the interrupting object(s) were completely featurally distinct from the doll representations being maintained, they did not go (or come from) behind the screen where the dolls were occluded, and they did not interact with the display in any way or appear in the final tableau. These experiments thus indicate that infants' persisting object representations can survive at least some types of *extrinsic* interruptions – a finding that is ecologically relevant to the project of determining how such abilities may operate in a real world filled with dynamic and haphazard overlapping objects and events.<sup>3</sup>

Infants' failure to maintain persisting object representations through the interruption in Experiment 2 is also independently important. This result demonstrates that the maintenance of such representations can be disrupted by allocating attention to *extrinsic* interrupting events that require the same attentional resources – such as the interrupting objects in Experiment 2, which resulted in a failure to discriminate the new number of dolls at test. Moreover, this finding provides evidence that visual attention in infancy is object-based and capacity-limited, since the disruption of infants' persisting object representa-

tions did not depend on the brute perceptual attributes of the interruption (which were controlled in these experiments) but rather on the presence of additional discrete objects. Because similar constraints have been observed in adult visual cognition, these data add to the mounting evidence that infants' performance in such tasks and adults' performance in mid-level vision experiments may reflect the same underlying processes (e.g. Carey & Xu, 2001; Chiang & Wynn, 2000; Feigenson, Carey & Hauser, 2002; Kaufman, Csibra & Johnson, 2005; Mitroff *et al.*, 2004, 2005, under review; Scholl, 2001; Scholl & Leslie, 1999; vanMarle & Scholl, 2003; Wynn & Chiang, 1998).

We propose that studies of the 'interruptibility' of infants' persisting object representations, as illustrated in this brief report, could be useful more generally as a way of characterizing the underlying nature of such processing. In particular, it will be interesting for future studies to focus explicitly on the capacity-limited nature of this system, by systematically varying both the number and complexity of object representations that can be simultaneously active. It may be, for example, that the limits observed in our study reflect both the number of objects present as well as their complexity or informational load. Thus, an interruption involving even a single object which was sufficiently complex could disrupt concurrent processing, despite the fact that infants' representations of the number of occluded objects survived the one-object interruption in Experiment 1. The global limit on which interruptions can be 'survived' may thus be object-based, but the capacity limit (i.e. the number of interrupting objects which can be survived) may be a 'moving target', dependent on both their salience and complexity. Indeed, similar limits have been observed in adult visual cognition, where processes such as visual working memory are limited both by the number of objects (Xu & Chun, 2006) and by their complexity (Alvarez & Cavanagh, 2004). In the context of our experiment, of course, such limits may have been especially severe, since attention and memory needed to span objects from two different events (i.e. the dolls and the interruption).

The 'interruptibility' method could also be used to ask other questions which are less related to capacity limits *per se*. For example, studies of what can disrupt the maintenance of object representations may help reveal which types of stimuli are processed and represented in terms of object-files: will an infant's persisting object representation be effectively impaired by a variable number of interrupting sounds (cf. Kobayashi, Hiraki & Hasegawa, 2005; Lipton & Spelke, 2003; vanMarle & Wynn, 2002), substances (Huntley-Fenner *et al.*, 2002) or by a variable number of puppet-actions (e.g. Sharon & Wynn, 1998)? In this way, studies of the 'interruptibility'

<sup>3</sup> Such abilities might be present in other types of situations in adult visual cognition. For example, adults' speed in selecting a target from an object array is not hampered when the search field is temporarily replaced (i.e. 'interrupted') by a different object configuration. The 'rapid resumption' of the initial search task strongly suggests that information is retained in visual short-term memory despite the onset of an additional (although very similar) interrupting event (Lleras, Rensink & Enns, 2005). The present results suggest that a similar ability is present in young infants even for events that are dramatically different from one another.

of infants' object representations may be used to characterize not only the underlying limits on object cognition, but *why* such limits do and do not obtain, interpreted in terms of underlying cognitive processes and resources.

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## References

- Aguiar, A., & Baillargeon, R. (1999). 2.5-month-old infants' reasoning about when objects should and should not be occluded. *Cognitive Psychology*, **39**, 116–157.
- Aguiar, A., & Baillargeon, R. (2002). Developments in young infants' reasoning about occluded objects. *Cognitive Psychology*, **45**, 267–336.
- Alvarez, G.A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science*, **15**, 106–111.
- Baillargeon, R., Spelke, E.S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition*, **20**, 191–208.
- Bonatti, L., Frot, E., Zangl, R., & Mehler, J. (2002). The Human First Hypothesis: identification of conspecifics and individuation of objects in the young infant. *Cognitive Psychology*, **45**, 1–39.
- Bremner, J.G., Johnson, S.P., Slater, A.M., Mason, U., Foster, K., Cheshire, A., & Spring, J. (2005). Conditions for young infants' perception of object trajectories. *Child Development*, **76**, 1029–1043.
- Carey, S., & Xu, F. (2001). Infants' knowledge of objects: beyond object-files and object tracking. *Cognition*, **80**, 179–213.
- Cherries, E.W., Mitroff, S.R., Wynn, K., & Scholl, B.J. (2005). Cohesion as a principle of object persistence in infants and adults [Abstract]. *Journal of Vision*, **5**, 1043a.
- Chiang, W.-C., & Wynn, K. (2000). Infants' tracking of objects and collections. *Cognition*, **77**, 169–195.
- Clearfield, M., & Mix, K. (1999). Number versus contour length in infants' discrimination of small visual sets. *Psychological Science*, **10**, 408–411.
- Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, **24** (1), 87–114.
- Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: evidence from infants' manual search. *Developmental Science*, **6**, 568–584.
- Feigenson, L., & Carey, S. (in press). On the limits of infants' quantification of small object arrays. *Cognition*.
- Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: object files versus analog magnitudes. *Psychological Science*, **13** (2), 150–156.
- Feigenson, L., Carey, S., & Spelke, E. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology*, **44**, 33–66.
- Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, **8**, 307–314.
- Flombaum, J.I., Kundey, S.M., Santos, L.R., & Scholl, B.J. (2004). Dynamic object individuation in rhesus macaques: a study of the tunnel effect. *Psychological Science*, **15**, 795–800.
- Flombaum, J.I., & Scholl, B.J. (in press). A temporal same-object advantage in the tunnel effect: facilitated change detection for persisting objects. *Journal of Experimental Psychology: Human Perception & Performance*.
- Halberda, J., Simons, D.J., & Wetherhold, J. (under review). Overcoming the three-item limit: Gestalt grouping principles explain increases in change detection capacity. Manuscript submitted for publication.
- Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: perceived rigidity and cohesiveness influence infants' representations of small numbers of discrete entities. *Cognition*, **85**, 203–221.
- Kaldy, Z., & Leslie, A.M. (2003). Identification of objects in 9-month-old infants: integrating 'what' and 'where' information. *Developmental Science*, **6**, 360–373.
- Kaldy, Z., & Leslie, A.M. (2005). A memory span of one? Object identification in 6.5-month-old infants. *Cognition*, **2**, 153–177.
- Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. Davies (Eds.), *Varieties of attention* (pp. 29–61). New York: Academic Press.
- Kahneman, D., Treisman, A., & Gibbs, B. (1992). The reviewing of object files: object-specific integration of information. *Cognitive Psychology*, **24**, 175–219.
- Kaufman, J., Csibra, G., & Johnson, M. (2005). Oscillatory activity in the infant brain reflects object maintenance. *Proceedings of the National Academy of Sciences, USA*, **102**, 15271–15274.
- Kobayashi, T., Hiraki, K., & Hasegawa, T. (2005). Auditory-visual intermodal matching of small numerosities in 6-month-old infants. *Developmental Science*, **8**, 409–419.
- Lipton, J.S., & Spelke, E.S. (2003). Origins of number sense. *Psychological Science*, **14**, 396–401.
- Lleras, A., Rensink, R.A., & Enns, J.T. (2005). Rapid resumption of interrupted visual search. *Psychological Science*, **16**, 684–688.
- Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, **390**, 279–281.
- Michotte, A., Thinès, G., & Crabbé, G. (1991). Amodal completion of perceptual structures. In G. Thinès, A. Costall & G. Butterworth (Eds.), *Michotte's experimental phenomenology of perception* (pp. 140–167). Hillsdale, NJ: Erlbaum. (Original work published 1964.)



- Mitroff, S.R., Scholl, B.J., & Wynn, K. (2004). Divide and conquer: how object files adapt when a persisting object splits into two. *Psychological Science*, **15**, 420–425.
- Mitroff, S.R., Scholl, B.J., & Wynn, K. (2005). The relationship between object files and conscious perception. *Cognition*, **96**, 67–92.
- Mitroff, S.R., Scholl, B.J., & Wynn, K. (under review). One plus one equals one: the effects of merging on object files. Manuscript submitted for publication.
- Pinto, J.P. (1996). XHAB (version 6.5): Experimental control software for MS-DOS [computer software]. Palo Alto, CA: Author.
- Pylyshyn, Z., & Storm, R. (1988). Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spatial Vision*, **2**, 179–197.
- Santos, L.R. (2004). ‘Core knowledges’: a dissociation between spatiotemporal knowledge and contact-mechanics in a non-human primate? *Developmental Science*, **7**, 167–175.
- Scholl, B.J. (2001). Objects and attention: the state of the art. *Cognition*, **80**, 1–46.
- Scholl, B.J., & Leslie, A. (1999). Explaining the infant’s object concept: beyond the perception/cognition dichotomy. In E. Lepore & Z. Pylyshyn (Eds.), *What is cognitive science?* (pp. 26–73). Oxford: Blackwell.
- Scholl, B.J., & Nevarez, H.G. (2002). Why so slow? The role of speed discontinuities in maintaining object persistence through occlusion. Talk given at the annual meeting of the Psychonomic Society, 22 November 2002, Kansas City, MO. [Abstract published in *Abstracts of the Psychonomic Society*, **7**, 19.]
- Scholl, B.J., & Pylyshyn, Z.W. (1999). Tracking multiple items through occlusion: clues to visual objecthood. *Cognitive Psychology*, **38**, 259–290.
- Scholl, B.J., Pylyshyn, Z.W., & Feldman, J. (2001). What is a visual object? Evidence from target merging in multi-element tracking. *Cognition*, **80**, 159–177.
- Scholl, B.J., & Xu, Y. (2001). The magical number 4 in vision. *Behavioral and Brain Sciences*, **24**, 145–146.
- Sharon, T., & Wynn, K. (1998). Infants’ individuation of actions from continuous motion. *Psychological Science*, **9**, 357–362.
- Spelke, E.S. (1998). Nativism, empiricism, and the origins of knowledge. *Infant Behavior and Development*, **21**, 181–200.
- Spelke, E.S. (2000). Core knowledge. *American Psychologist*, **55**, 1233–1243.
- Spelke, E.S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, **99**, 605–632.
- Spelke, E.S., Kestenbaum, R., Simons, D.J., & Wein, D. (1995). Spatiotemporal continuity, smoothness of motion and object identity in infancy. *The British Journal of Developmental Psychology*, **13**, 113–142.
- Tremoulet, P., Leslie, A.M., & Hall, G. (2000). Infant attention to the shape and color of objects: individuation and identification. *Cognitive Development*, **15**, 499–522.
- Uller, C., Carey, S., Huntley-Fenner, G., & Klatt, L. (1999). What representations might underlie infant numerical knowledge? *Cognitive Development*, **14**, 1–36.
- vanMarle, K., & Scholl, B.J. (2003). Attentive tracking of objects vs. substances. *Psychological Science*, **14**, 498–504.
- vanMarle, K., & Wynn, K. (2002). 7-month-old infants’ sensitivity to number in the auditory domain. Poster presented at the Society for Research in Child Development. Tampa, FL.
- Vogel, E.K., Woodman, G.F., & Luck, S.J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 92–114.
- Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, **358**, 749–750.
- Wynn, K., & Chiang, W.-C. (1998). Limits to infants’ knowledge of objects: the case of magical appearance. *Psychological Science*, **9**, 448–455.
- Xu, F., & Carey, S. (1996). Infants’ metaphysics: the case of numerical identity. *Cognitive Psychology*, **30**, 111–153.
- Xu, F., Spelke, E.S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, **8**, 88–101.
- Xu, Y., & Chun, M.M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, **440**, 91–95.

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