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PAPER

Cohesion as a constraint on object persistence in infancy

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Abstract

A critical challenge for visual perception is to represent objects as the same persisting individuals over time and motion. Across several areas of cognitive science, researchers have identified cohesion *as among the most important theoretical principles of object persistence: An object must maintain a single bounded contour over time. Drawing inspiration from recent work in adult visual cognition, the present study tested the power of cohesion as a constraint as it operates early in development. In particular, we tested whether the most minimal cohesion violation – a single object splitting into two – would destroy infants' ability to represent a quantity of objects over occlusion. In a forced-choice crawling paradigm, 10- and 12-month-old infants witnessed crackers being sequentially placed into containers, and typically crawled toward the container with the greater cracker quantity. When one of the crackers was visibly split in half, however, infants failed to represent the relative quantities, despite controls for the overall quantities and the motions involved. This result helps to characterize the fidelity and specificity of cohesion as a fundamental principle of object persistence, suggesting that even the simplest possible cohesion violation can dramatically impair infants' object representations and influence their overt behavior.*

Introduction

A key challenge in perception is to transform the undivided wash of visual input into representations not only of discrete objects, but also of objects that persist as the same individuals over time. One of the most well-developed frameworks for studying object persistence has come from studies of how and when young infants do and do not track objects as the same. These results have been summarized in terms of a set of 'core knowledge' principles that guide infants' understanding of their physical world and continue to provide the foundation of such abilities in adulthood (e.g. Carey & Spelke, 1996; Spelke, 2000; Spelke & Kinzler, 2007). For instance, from very early, infants expect that objects will continue to persist when out of sight (e.g. Baillargeon & DeVos, 1991; Baillargeon, Spelke & Wasserman, 1985; Shinskey & Munakata, 2003), must trace spatiotemporally continuous paths (Spelke, Kestenbaum, Simons & Wein, 1995), and must occupy physically distinct locations from other objects (Spelke, Breinlinger, Macomber & Jacobson, 1992).

Cohesion in infancy

One of the most powerful principles of 'core knowledge' is that of *cohesion*: an object must maintain a single bounded contour over time (e.g. Spelke, 1990, 1994). Even 3-month-olds assume that objects should maintain their connectedness while being manipulated and should move as a single entity (Spelke & Van de Walle, 1993). Indeed, this principle may be uniquely important in that it helps define what counts as an object in the first place. If you want to know what an object is, just 'grab some and pull'; the stuff that comes with your hand is the object, and the stuff that doesn't (and thereby fails to maintain a single unified boundary with the stuff that moved with your hand) is not. This has led some theorists to claim that cohesion is perhaps the single most important principle of what it means to be an object (e.g. Bloom, 2000; Pinker, 1997).

This suggests that while infants normally have robust expectations driven by core knowledge for how and when objects persist over time, these expectations should break down in the context of cohesion violations. And, indeed, this seems to be the case. At the same age that infants can successfully represent the precise number of objects that appear on a stage or that have disappeared behind an occluder, they fail to represent the quantity of a noncohesive substance (such as sand) poured onto the display in tasks that are otherwise identical (Huntley-Fenner, Carey & Solimando, 2002; Rosenberg & Carey, 2006). Moreover, infants not only fail to represent the *quantity* of a portion of matter violating cohesion, but even appear not to represent its *continued existence*: when shown a noncohesive pile of small Lego blocks moved, piece by piece, behind an occluder, infants fail to show surprise when the occluder is removed to reveal an empty stage behind it (Chiang & Wynn, 2000).

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Open questions

The infancy studies described above are, to our knowledge, the only ones that have directly explored cohesion as a principle constraining infants' ability to track objects over time. Several open questions remain. First, it remains unclear just what kinds of cues can trigger the operation of this type of principle. The above studies do involve cohesion violations, but of particularly extreme sorts: the use of a nonsolid substance (Huntley-Fenner *et al.*, 2002; Rosenberg & Carey, 2006) or the sequential dismantling of a pile into several parts (Chiang & Wynn, 2000). In principle, however, cohesion violations do not require such extremes. Indeed, even a single object broken in two violates cohesion – yet that hardly seems intuitively likely to disrupt infants' object representations, since they surely encounter objects being split apart frequently (e.g. foods such as cookies and bread, toys with multiple parts that join together and pull apart, and so on).

It also remains unclear just *why* cohesion violations impair infants' intuitions about object persistence. It could be that such violations are recognized as non-object behavior, triggering a re-categorization that then destroys the initial object representations. However, it is also possible that cohesion violations disrupt object representations for more specific reasons. For example, it may be that these cohesion violations inherently introduce some fleeting ambiguity that must be resolved by visual object tracking processes. Such processes may need to track objects as units with punctate spatiotemporal addresses (much as you might point to an object as it moves), but pouring nonsolid substances (as in Huntley-Fenner *et al.*, 2002) may have no ready anchor for such tracking. Similarly, the progressive dismantling of an object into several component pieces (as in Chiang & Wynn, 2000) may frustrate object tracking by removing a single salient anchor. This possibility suggests that cohesion violations may disrupt object processing less because of any inferred categorical status as a nonsolid substance, and more because of trackability (as argued by vanMarle & Scholl, 2003).

The current study

Here we ask whether infants' object representations are disrupted by the simplest possible cohesion violation: a single rigid object that splits into two rigid objects. It might be that previously observed impairments depended on the complexity of those displays, and the particular cues they provided to an entity's 'non-object' status. However, if cohesion truly operates as a 'principle' – that objects must maintain single unified boundaries over time – then even this simple violation should disrupt the underlying representations.

Though it may seem unlikely that such an apparently simple event would impair object processing, we drew inspiration in this regard from analogous studies of adult visual cognition. Studies of adults' object tracking have demonstrated impairments for objects that seem to 'pour' from one location to another (vanMarle & Scholl, 2003), but the principle of cohesion has also been tested in more direct ways. For example, one study showed that object-specific representations – or 'object files', as measured by the object-reviewing paradigm of Kahneman and Treisman (Kahneman & Treisman, 1984; Kahneman, Treisman & Gibbs, 1992) – are in fact disrupted when a single object is seen to smoothly split into two (Mitroff, Scholl & Wynn, 2004).

We thus adapted this 'splitting' manipulation (which was itself motivated by the developmental work described earlier) for use with infants as a strong test of whether the cohesion principle severely constrains how objects are represented early in development. Moreover, whereas previous studies of cohesion in infants relied on looking-time patterns as measures of expectations, we employed a manual choice paradigm that has the potential to reveal impairments in infants' overt behavior. By widening the range of tasks, we allow converging evidence from multiple methodologies to help reveal the nature of cohesion as a powerful constraint on infants' persisting object representations. We employed a forced-choice crawling procedure adapted from a previous study of infants' ability to represent relative numerical quantities (Feigenson, Carey & Hauser, 2002). In theses studies, infants witnessed one cracker placed into a large container, and two crackers placed into a different container, and were then allowed to crawl to one or the other. Without any further manipulation, infants crawled to the 2-cracker container, given its greater payoff (Feigenson *et al.*, 2002).

In our study, infants witnessed a single small graham cracker placed into one container, and a single large cracker broken into two pieces and then placed into a second container (see Figure 1a). A second group of infants saw this same event, except that the large cracker had already been pre-split (see Figure 1b). This control guaranteed that any difference in performance could only be attributed to the cohesion violation since the motion and timing of all hand movements were equated across conditions. If cohesion is a powerful principle of object persistence, the splitting of a single large cracker

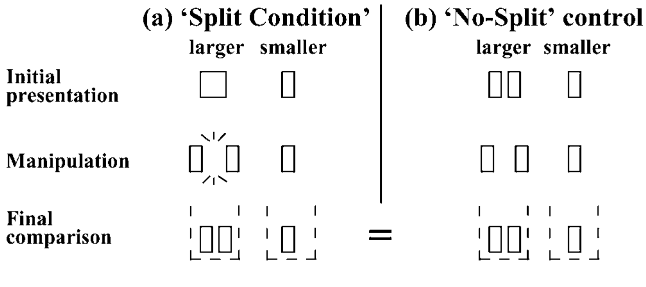

Figure 1 *A schematic depiction of the key events in the (a) Split condition and (b) No-Split condition. See the text for details.*

into two should disrupt infants' representations of the cracker quantity in each location, and thus render their choice random.

Method

Participants

We tested 52 locomoting, full-term 11-month-old infants recruited from the greater New Haven area. Half (13 males, 13 females; mean age = 10 months, 29 days; range = 10;2 to 12;12) participated in a *No-Split* control condition, while the other half (14 males, 12 females; mean age = 10 months, 29 days; range = 10;0 to 12;20) participated in a *Split* condition. Another 14 infants were tested but excluded from the analyses due to unwillingness to crawl (11 infants) or experimental error (three infants).

Stimuli and procedures

The experiment took place in a small, unfurnished room. The mother and infant sat on the floor approximately 2 m from the experimenter. The experiment began with a brief 'warm-up' trial in which the infant was shown a small toy being hidden inside an opaque cup (12 cm in diameter, 20 cm high). Both the experimenter and the mother encouraged the infant to crawl to the cup and retrieve the toy. This procedure was repeated until the infant succeeded.

Test trials began with the same setup, with the mother securely holding the infant in front of her on the floor. The experimenter retrieved two identical cups from behind his back, briefly shook them upside-down, and placed them right-side-up on the floor between himself and the infant. The cups were carefully spaced 1 m apart from one another and approximately 1.5 m from the infant, one to the left and one to the right of his or her midline. The experimenter demonstrated that the task involved food by retrieving a small piece of graham cracker from a container concealed in his lap and eating it while the infant watched. Each infant then saw the experimenter place 1 cracker in one cup and 2 crackers in the other (with order and location – left or right – counterbalanced across infants) as described below, and the infant was then encouraged to crawl to the cup of his or her choice.[1]

Split condition

For the 2-cracker placement, the experimenter reached into his lap and retrieved a single, 2-unit graham cracker (6.5 × 6.6 cm). He then held his hands (spaced 10 cm apart) above either the right or left cup (counterbalanced), with his left hand empty and his right hand holding the 2-unit cracker. He said 'Look!' and then grasped the other side of the cracker with his left hand and split it evenly into two single units while pulling both his hands (and the crackers) further apart (20 cm) and repeating 'Look!' He then placed the single-unit cracker from his left hand into the container, paused for 1 second, and placed the single-unit cracker from his right hand into the bucket. For the *1-cracker* placement in the other cup, the experimenter used identical hand motions (including 'faked' placements of nothing into one of the containers) to control for the amount of time and complexity involved in the presentation, as demonstrated in the online movies. The order and location of 1- and 2-cracker placement events was counterbalanced. After the crackers had been put into both cups, the experimenter immediately looked down (so as not to cue the baby) and said, 'Okay, which do you want?' after which the mother released the baby to crawl.

No-split condition

Infants in this condition saw identical events, except that they never saw a double-unit cracker: For the 2-cracker placement, the two single-units were already separated prior to the experimenter pulling them from the container in his lap. The experimenter thus removed two crackers (one in each hand) from his lap simultaneously, held them 10 cm apart, and then pulled both his hands (and the crackers) further apart (20 cm), before placing the crackers into the containers as described above. In this way, all the timing and hand movements were identical to those in the Split condition.

Infants were given a 10-second window to choose just one of the two locations (since they could not reach both simultaneously). Each infant participated in just a single trial.

Results

The results of the two conditions are depicted in Figure 2. A significant majority of infants in the No-Split condition chose the cup with the larger cracker quantity (20 of 26 infants; $p < .05$, two-tailed sign test). There was no difference between males and females, or cracker placement order. This result replicates previous work using this paradigm, showing that infants can successfully choose between hidden quantities of 1 versus 2 crackers (Feigenson *et al.*, 2002).

In contrast, infants in the Split condition chose randomly between the two containers (with 12 of the 26 infants choosing the container with the larger cracker quantity) and thereby performed significantly worse than those in the No-Split condition ($p < .05$, two-tailed Fisher's exact test). Since all hand motions and timing were identical in the two conditions, chance performance in the Split

[1] For online demonstrations of these trial types, see http://www.yale.edu/infantlab/splitting/

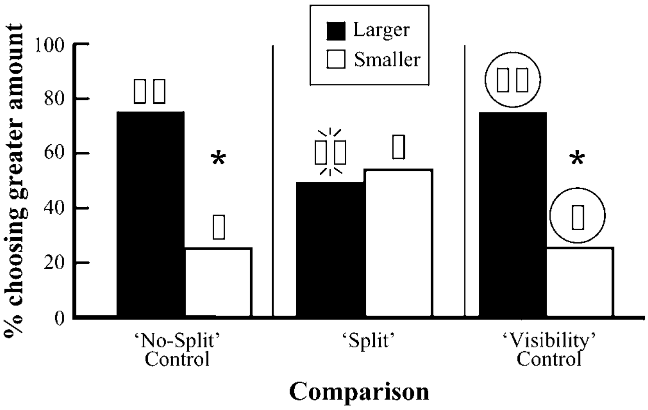

Figure 2 *The percentage of participants who chose the container with the larger amount of crackers in each condition.*

condition indicates that infants were unable to successfully represent and compare the cracker quantities when they witnessed one of the crackers split into two. This was the case even though the final comparison of what the infants saw enter the containers was identical in the two conditions (see Figure 1).

Visibility control

We argue that infants chose randomly in the Split condition because their representation of the single 2-unit cracker was disrupted by the cohesion violation that the splitting event entailed, and they were not able to reconstruct a viable representation before the crackers were placed into the containers that was sufficient to support an accurate comparison. If this impairment is due to a disruption of the object representation *per se*, then infants should have no trouble comparing two fully visible cracker amounts that have undergone the same manipulation. Alternatively, could it be that they simply found a 'split' cracker to be less intrinsically appealing – and therefore searched accordingly despite accurate representations of the cracker quantities in each container? To rule out this possibility, we conducted a 'visibility' control with a new group of 20 infants (10 males, 10 females; mean age = 10;15, range = 10;0 to 12;8). This group saw events identical to those in the Split condition, except that the crackers were placed onto plates rather than into opaque containers. If infants' previous failure was due to a preference for non-split crackers, then this change should make no difference, and the failure should replicate. But if their failure stemmed from an inability to accurately represent the relative quantities in the two locations, this manipulation should lead infants to succeed since all they need do is compare the fully visible crackers on the two plates.

In fact, the results of this condition exactly matched the successful outcome of the No-Split condition (see Figure 2): 15 of the 20 infants successfully chose the container with the larger cracker quantity ($p < .05$, two-tailed sign test), yielding significantly better performance than in the Split condition ($p < .05$, one-tailed Fisher's exact test).

Discussion

This study demonstrated that even the simplest possible cohesion violation – a single object splitting into two – will disrupt infants' persisting object representations. This effect could have obtained at several possible levels. Perhaps the most extreme interpretation of these results would be that the split completely destroyed (or caused infants to discard) their initial representation of the 2-unit cracker, while also making it difficult for them to construct new representations of the two single-unit crackers generated by the splitting, which were in full view for several seconds. (Indeed, follow-up studies could test how much time is necessary to allow the infants to successfully re-represent the split cracker as separate individuals.) However, it is also possible that infants' object representations of the double-cracker quantities were maintained, but the ability to use this representation in a comparative judgment was compromised. This is not implausible. Adults have been shown to possess certain visual information but not to employ that information in specific comparisons (Mitroff, Simons & Levin, 2004), and infants in other paradigms possess knowledge that they nevertheless fail to use for object individuation (Feigenson, 2005; Xu & Carey, 1996). Regardless of which of these two possible explanations is correct, however, these results seem important for several reasons:

First, these results suggest that cohesion is a powerful principle that operates over our early experience with objects. This is also consistent with the 'core knowledge' framework that also predicts continuity across the lifespan (Spelke, 2000; Spelke & Kinzler, 2007). Indeed, a previous study with adults demonstrated that a single object splitting into two imposed costs on visual processing (Mitroff *et al.*, 2004), but this may have resulted from a lifetime of experience with objects, and the statistical expectation that they would not split into two. The fact that we observed a similar (but even more devastating) effect in infants under 1 year old at minimum places an upper bound on the amount of experience required to give rise to such statistical knowledge, and is consistent with the possibility that this principle is truly a foundational aspect of visual processing (Spelke, 1998).

Second, these results demonstrate that deleterious effects of cohesion violations are not limited to complex displays involving the pouring of nonsolid substances (Huntley-Fenner *et al.*, 2002; Rosenberg & Carey, 2006) or collections of objects involving multiple parts and transformations (Chiang & Wynn, 2000). Rather, we find that even the simplest possible cohesion violation impairs infants' performance, via a seemingly pedestrian type of 'split' to a piece of food which infants may have encountered many times before. This impairment is especially notable since infants completely disregard many other types of salient changes – e.g. to objects' shapes or colors – or otherwise use them successfully to represent the correct number of objects involved in an event (McCrink & Wynn, 2004; Simon, Hespos & Rochat, 1995; Tremoulet, Leslie & Hall, 2000; Wilcox & Baillargeon, 1998; Wilcox & Chapa, 2004).

Third, these results demonstrate that the operation of a cohesion principle – and the results of cohesion violations – can impact real-world behavior. Previous studies of cohesion violations in infancy relied on looking-time measures as correlates of underlying expectations, but such measures have often proven controversial (e.g. Bogartz, Shinskey & Speaker, 1997). The disruptive consequences that we observed in the current study not only provide converging evidence with previous studies using looking-time measures, but also demonstrate that the cohesion principle operates powerfully enough to affect overt behavior.

Fourth, these results illustrate the power of the cohesion principle in infants' ability to maintain persisting object representations, since attending to a cohesion violation seems to have overwhelmed other possible strategies they could have used for discriminating the two amounts. For example, we know from previous work using the crawling paradigm that infants can discriminate the two choices based on the overall sizes of the crackers (Feigenson *et al.*, 2002). Similarly, infants in our study could have succeeded by comparing the overall area, volume, or continuous amount of the crackers in each bucket, either before or after the split, since the split-cracker side of the display (both when in view and then in the bucket) always contained twice the amount of cracker as the other side of the display. However, the cohesion violation in this study compromised infants' ability to use these continuous quantities – perhaps by destroying the object-based representations on which they depend, or by overwhelming the resources that are necessary for comparing the two amounts. These possibilities are being explored in several follow-up studies.

Finally, this experiment illustrates how research in infant cognition can benefit from interaction with research in adult visual cognition – and vice versa. In fact, the adult studies of cohesion violations (Mitroff *et al.*, 2004; vanMarle & Scholl, 2003) were entirely motivated by the initial work with infants (Chiang & Wynn, 2000; Huntley-Fenner *et al.*, 2002), and the present study has now taken the insights from these adult experiments and brought them back to infant research. Given their concordance, these results are also consistent with the possibility that these two literatures are in fact exploring the same underlying processes (Carey & Xu, 2001; Chiang & Wynn, 2000; Feigenson *et al.*, 2002; Scholl & Leslie, 1999).

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