Research Article

Psychological Science
2015, Vol. 26(7) 955–963

Reprints and permissions:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/0956797614547705
pss.sagepub.com

Object Persistence Enhances Spatial Navigation: A Case Study in Smartphone Vision Science

Brandon M. Liverence[1,2] and Brian J. Scholl[1]
[1]Yale University and [2]Northwestern University

Abstract
Violations of spatiotemporal continuity disrupt performance in many tasks involving attention and working memory, but experiments on this topic have been limited to the study of moment-by-moment on-line perception, typically assessed by passive monitoring tasks. We tested whether persisting object representations also serve as underlying units of longer-term memory and active spatial navigation, using a novel paradigm inspired by the visual interfaces common to many smartphones. Participants used key presses to navigate through simple visual environments consisting of grids of icons (depicting real-world objects), only one of which was visible at a time through a static virtual window. Participants found target icons faster when navigation involved persistence cues (via *sliding* animations) than when persistence was disrupted (e.g., via temporally matched *fading* animations), with all transitions inspired by smartphone interfaces. Moreover, this difference occurred even after explicit memorization of the relevant information, which demonstrates that object persistence enhances spatial navigation in an automatic and irresistible fashion.

Keywords
object persistence, spatial navigation, spatiotemporal continuity, virtual interfaces

Received 7/19/13; Revision accepted 7/4/14

People perceive dynamic events not only in terms of discrete objects, but in terms of individuals that persist from moment to moment, with such persistence computed on the basis of cues such as spatiotemporal continuity. Accordingly, such cues dramatically influence performance in many on-line perception tasks (for reviews, see Flombaum, Scholl, & Santos, 2009; Scholl, 2007). For example, people can track multiple moving objects through momentary occlusions, so long as the objects disappear and reappear gradually at occluding boundaries, but this ability disintegrates when objects gradually disappear and reappear at other boundaries (Scholl & Pylyshyn, 1999). Similarly, cues to object persistence influence perception during change detection (Flombaum & Scholl, 2006), visual crowding (Moore & Chung, 2013), and object-specific priming (Mitroff, Scholl, & Wynn, 2004), and even influence looking-time patterns in infants (Spelke, Kestenbaum, Simons, & Wein, 1995) and searching behavior by nonhuman primates (Flombaum, Kundey, Santos, & Scholl, 2004).

These and many other studies collectively suggest that persisting objects serve as fundamental units of perception, but are such effects limited to moment-by-moment, on-line visual representations? Here we report the first demonstration, to our knowledge, that object persistence also controls the construction of longer-term visual representations, as measured with a task requiring active spatial navigation through virtual environments.

Spatial Navigation in Virtual and Real Environments

Spatial navigation is surely one of the most fundamental cognitive abilities involving long-term visual representation, as it requires linking in memory objects and locations that are too distant to be viewed simultaneously.

Corresponding Authors:
Brandon M. Liverence, Department of Psychology, Northwestern University, Evanston, IL 60208-2710
E-mail: liverence@gmail.com

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

For example, after a brief tour of a new college campus, it might be impossible to know how to get from one just-visited distant location (say, the library) to another (say, a student center), but this task would be trivial for a student from that college. The same observation applies to the virtual environments that increasingly permeate modern life: For example, on smartphone interfaces, relevant objects (e.g., apps, folders) are spread across multiple spatially organized menus and "pages," only a subset of which are visible at any time.[1]

The current study was directly inspired by certain features of such virtual environments. As of this writing, all major smartphone operating systems require users to transition from virtual page to virtual page of applications and folders, using finger swipes that cause pages to slide into and out of view in a way that maintains object persistence. We explored the possibility that such features interact with visual processing so as to substantively enhance long-term memory and spatial navigation through smartphone environments.

Although much prior research has explored the cognitive and neural mechanisms of spatial navigation in real and virtual environments (for reviews, see Epstein, 2008; McNamara, Sluzenski, & Rump, 2008), no previous research (to our knowledge) has ever linked these processes to persisting object representations. One reason may be that in the real world, persistence cues are ubiquitous when objects transition in and out of view. For example, when one walks from one room to the next, objects always appear and disappear only by gradual "sliding." Although it is difficult in principle to manipulate object persistence in real-world environments, computerized environments inspired by smartphone interfaces may provide a model system for studying the role of object persistence in spatial navigation.

The Current Study

Here, we focus on spatial navigation through virtual environments consisting of grids of objects, learned by active exploration through multiple nonoverlapping views. We consider how such learning is influenced by cues to object persistence, and how such implicit representation does (or, to foreshadow our results, does not) interact with explicit memorization over longer time scales.

To explore these issues, we employed a novel experimental paradigm inspired by the page-based virtual environments ubiquitous in smartphone interfaces. Users of such interfaces navigate spatially organized gridlike pages of apps, via finger swipes, to find desired apps—and these layouts must be learned over time. Critically, page transitions can involve cues to persistence (e.g., when an old page slides smoothly out of view as the new page slides into view) or not (e.g., when pages change by fading out and in).[2]

In our experiments, participants used key presses to navigate through simple visual environments consisting of 4 × 4 grids of icons (see the example in Fig. 1a), only one of which was visible at any time through a static virtual window (depicted in Fig. 1b). Their task was to find four randomly selected target icons per trial, in order (as depicted in the lower region of Fig. 1b). Because a grid remained stable for dozens of trials, spatial learning could be measured as the decrease in searching time over those trials. We examined how such learning was influenced by cues to persistence, as realized by the nature of the dynamic visual transitions visible in the window. Each experiment contrasted two types of animations, one of which was displayed upon each valid key press as participants navigated the virtual environment.

Experiment 1: Sliding Versus Fading

This first experiment contrasted *slide-transition* and *fade-transition* animations (see Fig. 2a), which were presented in separate blocks. On all trials within a given block, the same icons were present in a stable arrangement, but entirely new icons were introduced on each subsequent block. In slide-transition blocks, each outgoing icon moved smoothly offscreen (in the appropriate direction) while the incoming icon moved smoothly on-screen; this led to a clear percept of the outgoing icon continuing to persist offscreen (as part of a larger, enduring spatial grid). In fade-transition blocks, each outgoing icon faded gradually out of view, and then the incoming icon faded gradually into view (with duration always equated between slide-transition and fade-transition animations). This condition included no cues to persistence, and so did not give rise to a percept of a larger gridlike structure. We measured rates of spatial learning to see if object persistence led to more efficient learning of the grids.

Method

Participants. Eighteen participants (12 female; mean age = 18.9 years) completed individual 40-min sessions and were compensated with course credit or a $10 payment. This sample size was fixed via pilot testing and then used for all subsequent experiments (except Experiment 4, as noted later).

Apparatus. Stimuli were presented (on a CRT monitor subtending 44.6° × 36.3°) using custom software written with MATLAB and the PsychToolbox libraries (Brainard, 1997; Pelli, 1997). Participants sat approximately 50 cm from the display. (All sizes reported are based on this distance.) Responses were made using the keyboard and mouse.

Stimuli and procedure. The icons were 64 photos of real-world objects (Brady, Konkle, Alvarez, & Oliva,

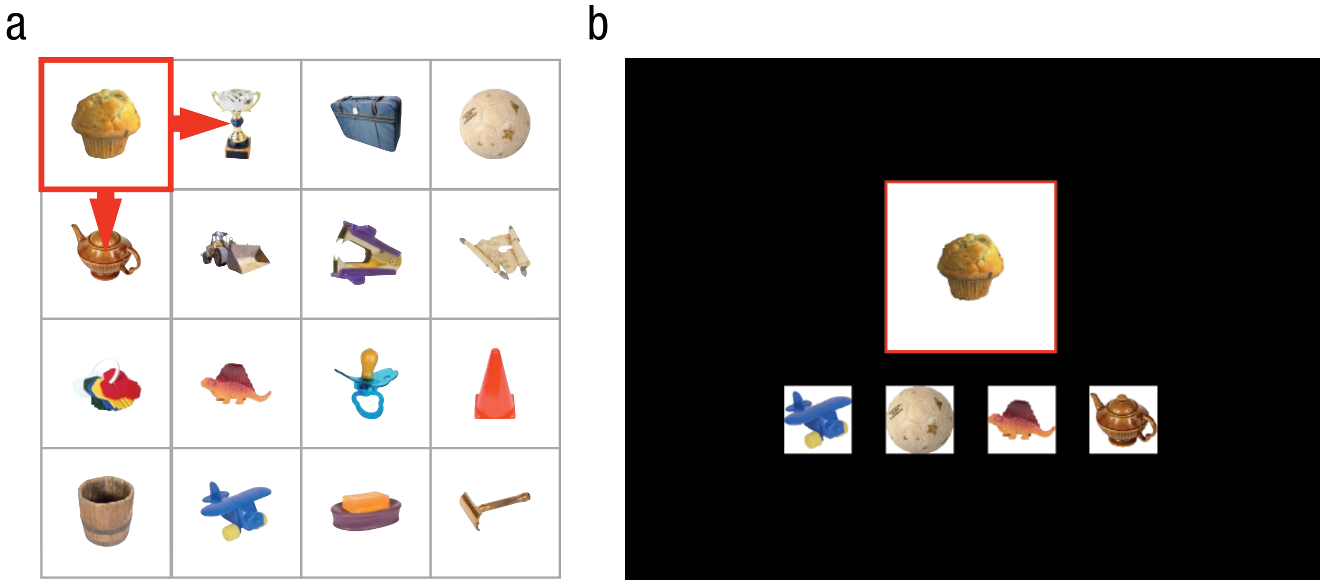

Fig. 1. Depictions of the stimuli and virtual layouts used in the experiments. The illustration in (a) is an example of a virtual 4 × 4 grid of icons that participants had to learn. The icons were shown one at a time through a static virtual window (indicated here in red; the gray lines, which were not visible during the actual experiments, demarcate the different virtual cells in the grid). The illustration in (b) is a screenshot from an actual trial involving this grid. The virtual window was presented centrally, and participants pressed keys to change which icon was displayed in the window, as they tried to locate and click on four target icons in order (as indicated by the illustrations below the window). Example animations illustrating the transitions between icons (in all conditions of all experiments) can be viewed online at http://www.yale.edu/perception/persistence-navigation/.

2008). Sixteen unique icons were used for each of four blocks. Each icon subtended roughly 3.99° (though each had a unique shape) and was presented at the center of the display inside a white square window (presented on a black background) that measured 9.96° on each side and was surrounded by a thin (0.16°) visible border.

Participants pressed four keys (for "up," "down," "left," and "right") to navigate through each 4 × 4 virtual environment (Fig. 1a). Upon each key press, the current icon was replaced inside the static window with the new corresponding icon (via a 400-ms animation during which no other key presses were possible). The grid was functionally bounded (e.g., so that a "right" key press had no effect if the current icon was from the right-most virtual column). On slide-transition trials, outgoing and incoming icons moved smoothly in the direction opposite the key press at a rate of 24.57° per second; because successive pages were separated by a center-to-center distance of 9.96°, this entire animation lasted 400 ms. On fade-transition trials, the current icon faded gradually to white over 167 ms; a blank white window was then displayed for 66 ms, and then the new icon gradually faded in from white over 167 ms (for a total of 400 ms).

On each trial, four *target* icons were displayed beneath the window (Fig. 1b), and participants had to locate and click on them in the order in which they were displayed (from left to right). The order and identity of the target icons for each trial were randomly generated once and stored offline, and these trials were then presented in a uniquely randomized order for each participant. After a correct click, a green border (0.24°) appeared around the image of the target icon. Out-of-order (i.e., incorrect) clicks were not registered.

Design. Four separate 4 × 4 grids were generated, and each was used in a separate block. Each participant completed 50 trials per block. The target icons changed on each trial, but the grid remained stable throughout the entire block. The order in which the grids were presented was the same for all participants (so that, e.g., the first block always involved the grid depicted in Fig. 1a). The animation type alternated between blocks (either slide-fade-slide-fade or fade-slide-fade-slide), with the order counterbalanced across participants.

Results and discussion

The initial two trials of each block were not analyzed, as pilot testing suggested that participants typically made an especially large number of key presses during those initial trials (a pattern consistent with subjective reports of a period of free exploration). In addition, trials with response times (RTs) longer than 30 s (0.56% of the remaining trials) were excluded.

The primary dependent measure was trial RT: the time elapsed from the beginning of a trial to when the participant clicked on the fourth target icon. These RTs, averaged over the two blocks for each condition, are depicted

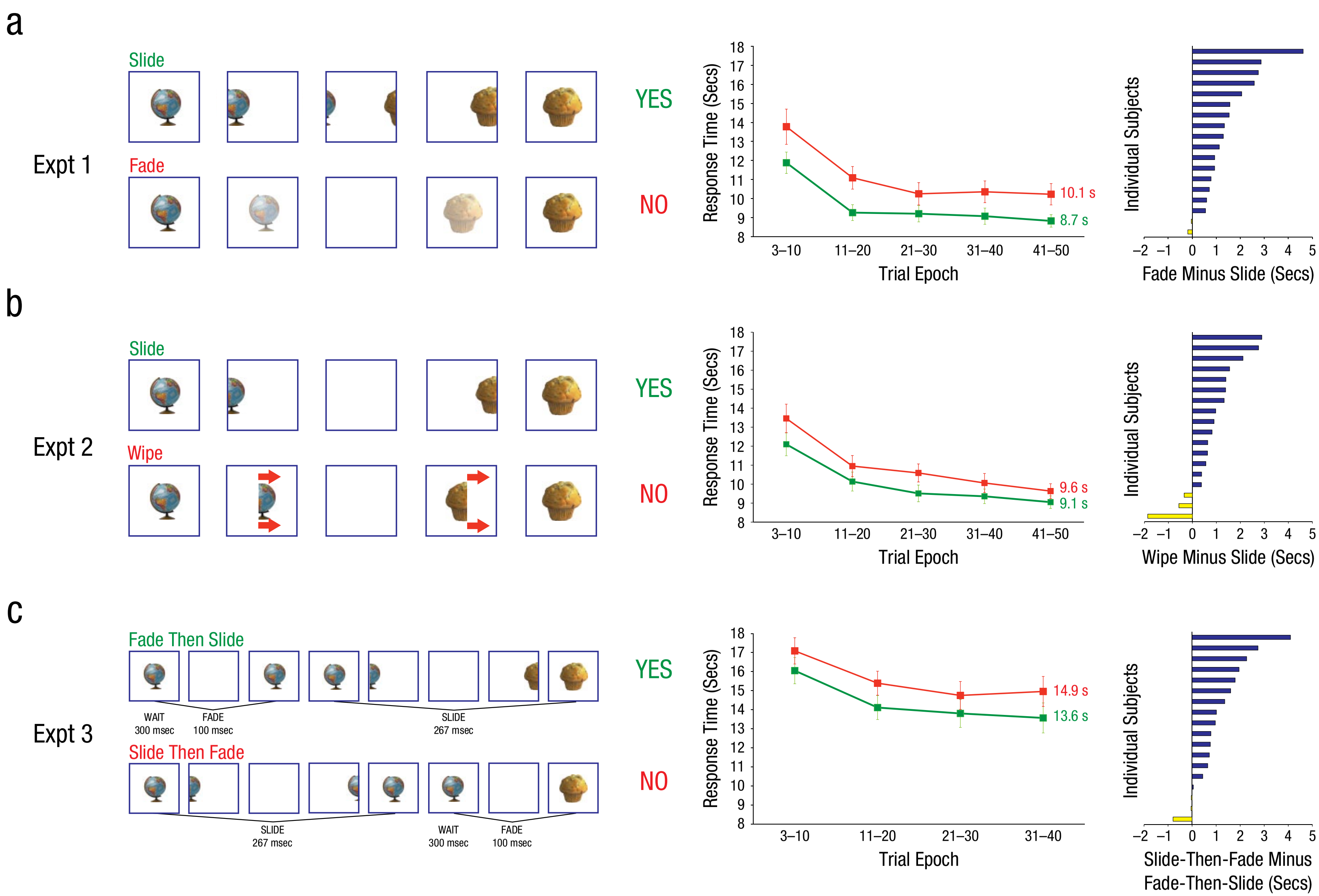

Fig. 2. Animations and data from (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3. The illustrations in the leftmost column depict the two types of transition animations that were contrasted in each experiment. The red arrows in the wipe-transition condition of Experiment 2 illustrate the motion direction of the invisible occluding surfaces; they were not actually shown to participants. The second column indicates whether each condition involved a cue to object persistence ("Yes") or not ("No"). The line graphs in the third column show response time averaged over observers (separately for each condition) as a function of trial epoch; the graphed lines are color-coded to match the corresponding condition labels. Error bars depict ±1 *SEM*. The bar graphs in the rightmost column depict the average difference in response time between the persistence and nonpersistence conditions for individual participants (rank-ordered from top to bottom by magnitude of this difference, with blue bars indicating differences in the dominant direction).

(binned into five 10-trial epochs) in Figure 2a. Spatial learning is clearly evident from the downward RT × Trial Epoch slope: RTs decreased by 3.31 s (25.8%) from the first to the last epoch. As is also clear from the separation between the two lines in this graph, object persistence had an extremely robust effect. Across all trials, participants were on average 1.41 s faster per trial on slide-transition blocks than on fade-transition blocks (9.27 s vs. 10.68 s, a difference of 15.2%), $t(17) = 5.22$, $p < .001$, $d = 1.23$. This difference was also highly robust nonparametrically: As depicted in the rightmost column of Figure 2a, 16 of the 18 participants were faster on slide-transition blocks than on fade-transition blocks.

The advantage for slide-transition blocks persisted even during the last 10-trial epoch of each block: Thus, even after much explicit memorization had already taken place (an issue explored directly in Experiment 4), there was still a robust difference between slide-transition and fade-transition RTs (8.67 s vs. 10.13 s), $t(17) = 4.08$, $p < .001$, $d = 0.96$. This suggests that the differences between these conditions with respect to object persistence cannot be overcome by explicit learning. Perhaps most surprising is the fact that even though performance clearly reached plateau after the second epoch in both conditions, RT differences were observed in every epoch thereafter (all ps ≤ .001). This is striking because in such simple environments, explicitly memorizing each icon's location should be trivially easy. Thus, these differences may ultimately reflect disruptions in implicit spatial representations, or a more general impairment in the ability to access spatial representations.[3]

Experiment 2: Sliding Versus Wiping

During slide-transition animations in Experiment 1, icons were always drawn as fully saturated, but their shapes were revealed only gradually as they appeared and disappeared. During fade-transition animations, however, the icons' shapes were visible throughout the animation sequence, though the icons were not fully saturated during the actual fading. Could such low-level differences in moment-to-moment visibility (rather than differences in object persistence) explain the robust difference between slide-transition and fade-transition RTs? To answer this question, we used a *wipe-transition* animation that was perfectly equated to the slide-transition animation in frame-by-frame visibility but disrupted object persistence (as in the analogous reverse virtual-occlusion wiping used by Scholl & Pylyshyn, 1999).

Method

This experiment was identical to Experiment 1 except as noted here. Eighteen new participants were tested (4 female; mean age = 19.2 years). The distances between icons in the virtual grid were 13.91°, and icons moved at 33.91° per second during slide-transition animations. During wipe-transition animations (depicted in the left column of Fig. 2b), the outgoing object gradually disappeared (and the incoming object gradually appeared) from one side to the other, as during slide-transition animations (so that moment-by-moment visibility was equated), but without actually moving. For example, a "right" key press caused the outgoing object to disappear as if it were gradually occluded by an invisible wall moving left to right—and after that object disappeared, the incoming object appeared as if it were gradually disoccluded from behind an invisible wall moving left to right.

Results and discussion

The results were analyzed exactly as in the previous experiment, and 0.41% of trials were excluded. The trial RTs (depicted in Fig. 2b) clearly replicated both the overall spatial learning and the robust difference between animation types observed in Experiment 1. RTs decreased by an average of 3.44 s (26.9%) from the first to last epoch. Across all trials, participants were on average 885 ms faster per trial on slide-transition blocks than on wipe-transition blocks (9.93 s vs. 10.82 s, a difference of 8.9%,), $t(17) = 3.29$, $p = .004$, $d = 0.78$, and the difference between conditions persisted in the final epoch (9.05 s vs. 9.64 s), $t(17) = 3.04$, $p = .007$, $d = 0.72$. The slide-transition advantage was also highly robust nonparametrically: As depicted in the rightmost column of Figure 2b, 15 of the 18 participants were faster on the slide-transition blocks than on the wipe-transition blocks. These results rule out the possibility that low-level visibility differences explain the difference in performance between the slide-transition and fade-transition conditions in Experiment 1.

Experiment 3: Controlling for Low-Level Motion

Whereas slide-transition animations involved motion in the direction opposite to each key press, fade-transition animations involved no motion whatsoever, and wipe-transition animations involved a more ambiguous motion signal (of the invisible occluder). Could such low-level differences in motion signals explain the observed effects? To answer this question, we created two new duration-matched conditions that each involved both a sliding phase and a fading phase (depicted in the leftmost column of Fig. 2c). In each condition, the initial icon disappeared twice—being replaced first with itself and then with the incoming icon. On slide-then-fade blocks, the icon was replaced by itself as in standard slide-transition animations and then was replaced by the incoming icon as in fade-transition animations from Experiment 1, so that persistence was disrupted for the critical transition. On fade-then-slide blocks, this order was reversed, so that persistence was maintained for the critical transition. The functional consequence was that the two conditions were equated for all low-level visual properties (including motion) and were equally unfamiliar to participants, yet still varied in persistence during the critical transition to the incoming icon.

Method

This experiment was identical to Experiment 1 except as noted here. Eighteen new participants were tested (7 female; mean age = 19.4 years). The same 64 photos were reshuffled into four new 4 × 4 grids. Transition animations now lasted 667 ms each. During fade-then-slide animations, an initial delay of 300 ms was followed by a 50-ms phase during which the outgoing icon gradually faded to white, then another 50-ms phase during which the outgoing icon gradually faded back in from white, and finally a 267-ms phase during which the outgoing icon was replaced by the incoming icon as in the slide-transition animations of Experiments 1 and 2. Slide-then-fade animations began with a 267-ms phase during which the outgoing icon was replaced by itself as in the slide-transition animation of Experiments 1 and 2; following a 300-ms delay, two 50-ms fading animations were presented, this time with the outgoing icon fading away and the incoming icon fading in. To account for the cumulative effect of longer transition times, we reduced the number of trials per block to 40 (for a total of 160 trials).

Results and discussion

The results were analyzed as in the previous experiments, and 2.27% of trials were excluded. The trial RTs (depicted in Fig. 2c) clearly replicated both the overall spatial learning and the robust difference between animation types observed in Experiments 1 and 2. RTs decreased by an average of 2.31 s (13.9%) from the first to last epoch. Across all trials, participants were on average 1.13 s faster per trial on fade-then-slide blocks than on slide-then-fade blocks (14.25 s vs. 15.38 s, a difference of 7.9%), $t(17) = 4.13$, $p < .001$, $d = 0.97$, and the difference between conditions persisted in the final epoch (13.56 s vs. 14.88 s), $t(17) = 3.08$, $p = .007$, $d = 0.72$. This difference was also highly robust nonparametrically: As depicted in the rightmost column of Figure 2c, 15 of the 18 participants were faster on fade-then-slide blocks than on slide-then-fade blocks. This pattern of results again points to an enhancement of spatial learning, and of performance after this learning has reached asymptote, for navigation involving visual cues to object persistence—even with familiarity and lower-level motion signals equated across conditions.

Experiment 4: Probing Explicit Memory

Perhaps the most striking result of the first three experiments was that the *persistence advantage* itself persisted throughout each experimental block—even through the last epoch. This is surprising because participants had presumably explicitly memorized the location of each icon in the virtual grid by the end of each block, so we had expected that any persistence-fueled difference between conditions would abate over time as explicit memory took over. In our final experiment, we tested this presumption explicitly, by replicating Experiment 1 but asking each participant to reconstruct the grid from memory after each block.

Method

The primary navigation task was identical to that of Experiment 1 except that (a) the distances between the icons were as in Experiment 2 and (b) there were 40 trials per block. To compensate for the reduced number of trials (and therefore, reduced power) in this experiment, we tested 22 new participants (19 female; mean age = 21.0 years).

After each block, participants completed a secondary memory task. An empty 4 × 4 grid of white square cells (each 4.99° on a side, with cells separated by 0.24° gray lines) was presented at the center of the display. Below this grid, the 16 icons from the just-completed block were randomly arranged in two rows, each icon separated by 4.99° from its neighbors. Participants were instructed to fill in the empty grid according to their memory of the configuration from the just-completed block by using the mouse to drag each icon into place. An initial click selected an icon, and a second click dropped it into place (as long as it had been moved to an empty cell). Accuracy was emphasized over speed, and responses were not final until the 16th icon was dropped into the grid (so that participants were free to rearrange already-assigned icons).

Results and discussion

The results of the primary navigation task were analyzed as in the previous experiments, and 1.20% of trials were excluded. The trial RTs (depicted in Fig. 3a) clearly replicated both the overall spatial learning and the robust difference between animation types observed in Experiments

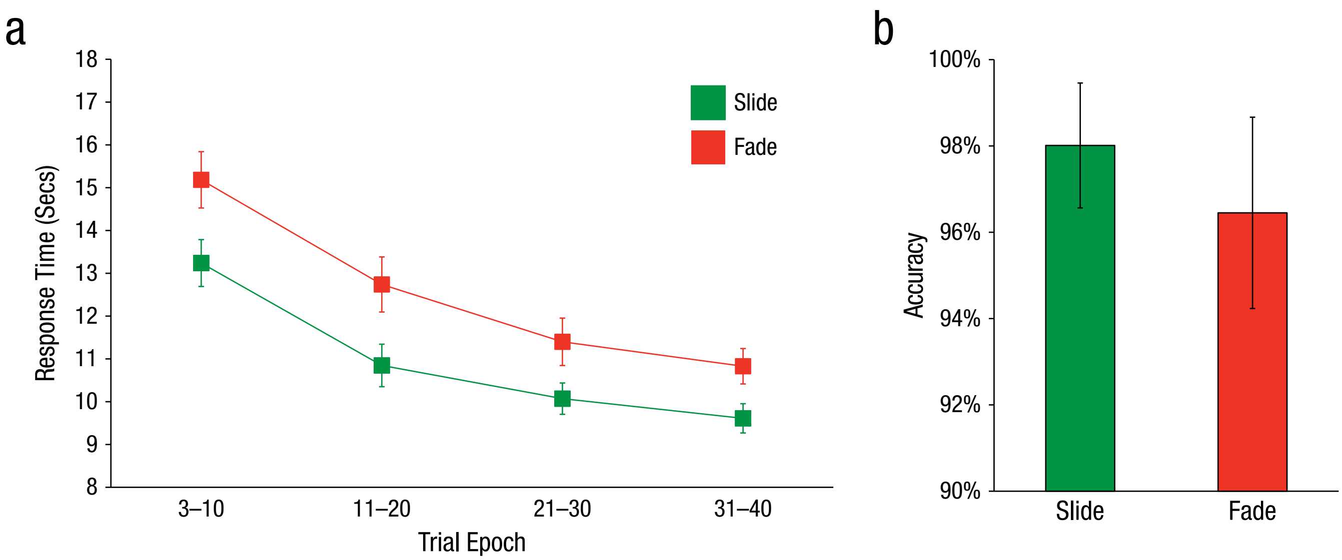

Fig. 3. Data from the slide-transition and fade-transition conditions of Experiment 4: (a) average response time from the primary spatial navigation task as a function of trial epoch and (b) average accuracy in the explicit memorization task that followed each block. Error bars depict ±1 *SEM*.

1 through 3. RTs decreased by an average of 3.99 s (28.1%) from the first to last epoch. Across all trials, participants were on average 1.51 s faster per trial on slide-transition blocks than on fade-transition blocks (10.81 s vs. 12.32 s, a difference of 14.0%), $t(21) = 5.02$, $p < .001$, $d = 1.07$, and the difference between conditions persisted in the final epoch (9.61 s vs. 10.83 s), $t(21) = 3.89$, $p < .001$, $d = 0.83$. The slide-transition advantage was also highly robust nonparametrically: Twenty of the 22 participants were faster on slide-transition blocks than on fade-transition blocks.

Memory-task accuracy was quantified as the number of icons correctly assigned to their respective grid cells, divided by 16, and averaged by condition. As is clear from Figure 3b, overall memory performance was nearly perfect for both slide-transition (98.0%) and fade-transition (96.5%) blocks (with less than a single error on average per subject per block), and accuracy did not differ between these conditions, $t(21) = 1.35$, $p = .19$, $d = 0.29$. As discussed in more detail in the General Discussion, this pattern of results suggests that the formation of explicit memory representations is not impaired by disruptions to object persistence—and accordingly, that the impairments on non-slide-transition trials may reflect a more implicit but still very functional type of long-term spatial memory. This possibility is also consistent with the fact that on the primary navigation task, the RT difference between persistence-preserving and persistence-disrupting conditions was apparent even in the first epoch of each experiment—which suggests that the observed effects do not simply reflect differences in the gradual accumulation of explicit spatial knowledge over the course of many trials of learning.

General Discussion

The four experiments presented here collectively demonstrate that cues to object persistence (realized via slide-transition and fade-then-slide animations) enhance spatial navigation and learning relative to manipulations that disrupt persistence (fade-transition, wipe-transition, and slide-then-fade animations). In particular, cues to object persistence led participants to navigate faster to their target objects. This difference was not due to visibility (equated in Experiment 2), motion signals (equated in Experiment 3), or differences in explicit memorization (probed explicitly in Experiment 4).

This persistence advantage was especially robust in both statistical and theoretical terms. Statistically, the advantage was apparent for all four experiments (i.e., RTs averaged over all trials), for all final epochs, and for 86.8% of participants. Theoretically, it seems important that the advantage persisted through the final epochs, after performance had reached plateau. This suggests that the persistence advantage is foundational, as seemingly no amount of learning can overcome it.

The persistence advantage also cannot be explained by appeal to familiarity, for two reasons. First, the two conditions used in Experiment 3 effectively controlled for familiarity: The fade-then-slide and slide-then-fade conditions would have been equally unfamiliar to our participants, and yet these conditions still yielded robust differences in navigation performance. Second, each experiment was reasonably long, and each participant viewed thousands of individual transitions. If the results were simply due to familiarity, we would expect the RT difference to have weakened over time, but it did not.

Underlying mechanisms: construction versus access

What is the mechanism by which object persistence enhances spatial navigation? In pondering this question, it seems especially relevant to bear in mind that this enhancement occurred despite explicit spatial memorization that was at or near ceiling (as measured in Experiment 4). This suggests two possible mechanisms, both of great interest.

First, the persistence advantage might reflect not the speed or fidelity of learning itself, but rather the *expression* of that learning in some contexts. In particular, disrupting object persistence might lead to learned spatial representations that are as robust as those acquired under conditions of object persistence (as reflected in explicit memory performance) even while such disruption impairs *access* to those representations during on-line navigation performance (perhaps because new object representations must be re-created after each continuity violation).

Second, the persistence advantage might indeed reflect slower or worse learning when persistence is disrupted, but involve spatial representations distinct from those that fuel explicit recall. This account would entail the existence of two types of spatial representation—perhaps implicit versus explicit representations, corresponding to the implicit/explicit distinctions in long-term memory more broadly (for reviews, see Schacter, 1987; Schacter, Chiu, & Ochsner, 1993). Explicit spatial representations might be especially accurate in a declarative sense but slower or less flexible to use during active navigation, whereas implicit representations might be less accurate but more easily used during active navigation (cf. Janzen & van Turennout, 2004).

Connections to real-world navigation

Although our data suggest that object persistence enhances navigation through virtual 2-D environments, it is clear that real-world navigation engages more complex processes. Studies involving disoriented-search tasks, for example, have revealed that whereas young children rely exclusively on geometric cues (e.g., 3-D environmental shape; Hermer & Spelke, 1994), older children and adults can also utilize visual landmarks (e.g., colored walls). These results suggest that there may be at least two independent systems for spatial navigation (Lee & Spelke, 2010). It is not obvious how either of these systems could have contributed to performance in our experiments, though, because the virtual environments we used contained no external landmarks or visible geometry. Nonetheless, it seems plausible that object persistence also enhances spatial navigation in real-world environments, given that persistence is such a ubiquitous feature of real-world perceptual experience (and given the unlikelihood of 2-D-specific mechanisms to have evolved).

Implications for interface design

Although the current project was a basic-science exploration of human spatial representation, we hope that principles of visual cognition revealed in such experiments can be used to inform interface design. In fact, smartphone interface design has become a major area of intellectual-property development (and litigation) in recent years (see Lohr, 2012). On one hand, our results suggest that interface animations are not simply "eye candy" but have substantive implications for usability. On the other hand, our results may help to explain why different groups could readily converge on similar designs, given that these designs may simply be best matched to the nature of human visual processing.

Conclusions

Objects persist even when out of view (for a philosophical review, see Scholl, 2007). Accordingly, object representations in the human visual system also appear to persist even when their corresponding objects are momentarily invisible. Previous work on the nature of such persisting representations has emphasized their influence in on-line perception during passive viewing, but the present results suggest that they are also deeply tied to longer-term spatial representations during active navigation.

Author Contributions

B. M. Liverence and B. J. Scholl designed the research and wrote the manuscript. B. M. Liverence conducted the experiments, and analyzed the data with input from B. J. Scholl.

Acknowledgments

For helpful conversation and comments on earlier drafts, we thank Marvin Chun, Marcia Johnson, Frank Keil, and Greg McCarthy.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Notes

1. We use the term *virtual* to denote computerized visual environments generally (including those of smartphone interfaces), rather than only 3-D "virtual reality" interfaces.
2. As of this writing, slide-transition animations are mandatory on Apple's iPhone interface, but fade-transition animations are an option in Google's Android operating system.

3. Because most smartphone interfaces have multiple app icons per virtual page, we also replicated this experiment using displays with virtual 3 × 3 grids of pages, each of which contained a 2 × 2 grid of icons, and we obtained the same patterns of results.

References

Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences, USA*, *105*, 14325–14329.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.

Epstein, R. A. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in Cognitive Sciences*, *12*, 388–396.

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. (2006). A temporal same-object advantage in the tunnel effect: Facilitated change detection for persisting objects. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 840–853.

Flombaum, J. I., Scholl, B. J., & Santos, L. R. (2009). Spatiotemporal priority as a fundamental principle of object persistence. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 135–164). New York, NY: Oxford University Press.

Hermer, L., & Spelke, E. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*, 57–59.

Janzen, G., & van Turennout, M. (2004). Selective neural representation of objects relevant for navigation. *Nature Neuroscience*, *7*, 673–677.

Lee, S. A., & Spelke, E. (2010). Two systems of spatial representation underlying navigation. *Experimental Brain Research*, *206*, 179–188.

Lohr, S. (2012, August 26). A patent war in your pocket. *The New York Times*, p. A4.

McNamara, T. P., Sluzenski, J., & Rump, B. (2008). Human spatial memory and navigation. In J. H. Byrne (Editor-in-Chief) & H. L. Roediger, III (Vol. Ed.), *Learning and memory: A comprehensive reference. Vol. 2. Cognitive psychology of memory* (pp. 157–178). Oxford, England: Elsevier.

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.

Moore, C. M., & Chung, A. (2013, May). *The role of perceptual organization in crowding*. Paper presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Schacter, D. L. (1987). Implicit memory: History and current status. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 501–518.

Schacter, D. L., Chiu, C. Y. P., & Ochsner, K. N. (1993). Implicit memory: A selective review. *Annual Review of Neuroscience*, *16*, 159–182.

Scholl, B. J. (2007). Object persistence in philosophy and psychology. *Mind & Language*, *22*, 563–591.

Scholl, B. J., & Pylyshyn, Z. W. (1999). Tracking multiple items through occlusion: Clues to visual objecthood. *Cognitive Psychology*, *38*, 259–290.

Spelke, E. S., Kestenbaum, R., Simons, D. J., & Wein, D. (1995). Spatiotemporal continuity, smoothness of motion and object identity in infancy. *British Journal of Developmental Psychology*, *13*, 113–142.