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The one-is-more illusion: Sets of discrete objects appear less extended than equivalent continuous entities in both space and time

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ABSTRACT

We distinguish between discrete objects and continuous entities in categorization and language, but might we actually *see* such stimuli differently? Here we report the *one-is-more illusion*, wherein 'objecthood' changes what we perceive in an unexpected way. Across many variations and tasks, observers perceived a single continuous object (e.g. a rectangle) as longer than an equated set of multiple discrete objects (e.g. two shorter rectangles separated by a gap). This illusion is phenomenologically compelling, exceptionally reliable, and it extends beyond space, to time: a single continuous tone is perceived to last longer than an equated set of multiple discrete tones. Previous work has emphasized the importance of objecthood for processes such as attention and visual working memory, but these results typically require careful analyses of subtle effects. In contrast, we provide striking demonstrations of how perceived objecthood changes the perception of other properties in a way that you can readily see (and hear!) with your own eyes (and ears!).

1. Introduction

One of the most fundamental and pervasive distinctions in cognitive science is that between the continuous and the discrete. Indeed, one of the key insights of the cognitive revolution was that intelligent behavior could be explained in part by appeal to discrete symbolic representations, even when the neural implementations of those discrete symbols might themselves be continuous (for seminal reviews see Newell, 1980; Pylyshyn, 1984). In cognitive psychology, this distinction has inspired spirited debate about the mechanisms of learning — where continuous, gradual processes (such as long-term potentiation) are contrasted with approaches that rely on storing and updating the values of discrete variables (e.g. Gallistel, 2000). And in developmental psychology, language researchers have sought to understand how the child's mind turns a continuous stream of syllables into representations of discrete words (e.g. Saffran, Aslin, & Newport, 1996).

Perhaps nowhere, though, has the distinction between the continuous and the discrete been more salient in cognitive science than in the study of perception. Sometimes this distinction is drawn explicitly, for example when asking about the temporal resolution of perception (e.g. VanRullen & Koch, 2003; see also Asplund, Fougnie, Zughni, Martin, & Marois, 2014). In other cases, the distinction is just as fundamental, but more implicit. For example, arguably the two most active areas in the study of visual cognition over the past two decades have been visual working memory and attention — and in both of these areas, this distinction has been central. The underlying units of visual working memory, for example, have been characterized as both discrete (limited by the number of 'slots' corresponding to encoded objects, regardless of their features; e.g. Luck & Vogel, 1997) and as continuous (limited by the overall amount of encoded information, regardless of how that information is distributed among objects; e.g. Alvarez & Cavanagh, 2004), and this remains an area of active debate (for a review, see Suchow, Fougnie, Brady, & Alvarez, 2014). And visual selective attention has similarly been characterized as both continuous (operating akin to a spotlight that selects undifferentiated spatial regions of the visual field; for a review, see Cave & Bichot, 1999) and discrete (selecting and shifting among individual objects rather than spatial regions; for a review, see Scholl, 2001).

One seemingly awkward aspect of these various theories, however, is that despite being theories of perception (and thus of seeing), the relevant effects cannot typically be seen. Instead, these effects (e.g. 'same-object-advantages' in object-based attention; e.g. Egly, Driver, & Rafal, 1994) are often relatively small, and only come out in the statistical wash. As such, the present experiments asked (for the first time, to our knowledge): does this sort of 'objecthood', beyond influencing attention and memory, also affect what we see in the first place?

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1.1. The current study

The eight experiments below introduce the *one-is-more illusion*, wherein observers perceive a single continuous object as *longer* than an equivalent set of multiple discrete entities. We first show (in Experiments 1a, 1b, 2a, 2b, and 2c) that this is true of perceived spatial extent: a single continuous object (such as a long rectangle) is perceived as longer than an equivalent set of multiple discrete entities (such as two shorter rectangles separated by a small gap). We further show (in Experiments 3a, 3b, and 4) that this effect extends beyond the perception of space (in vision) to the perception of time (in audition): a single continuous auditory tone is perceived as lasting longer than an equivalent set of discrete tones. In all cases, these effects persist even when equating for various lower-level stimulus properties. Collectively, these results show how the distinction between continuous and discrete entities has striking consequences for perceptual experience itself.

2. Experiment 1a: spatial extent (comparison)

We first demonstrated the one-is-more illusion in what may be the most direct possible way: observers viewed two stimuli on each trial — one a single continuous object, and the other a set of multiple discrete objects — and reported which was longer (from its leftmost point to its rightmost point). A typical display is depicted in Fig. 1 — where the images in each corner are equally long, but the single continuous rectangle appears longer. We also tested several other shapes, as depicted in Fig. 2.

2.1. Method

2.1.1. Participants

Ten naïve observers from the New Haven, Connecticut, community completed the experiment in exchange for course credit or a small monetary payment. The sample size was chosen based on independent pilot data, and was identical for all of the in-lab experiments using this same paradigm that are reported here. (As will become clear below, the effects we report are all exceptionally robust, such that all of our experiments were greatly overpowered to detect them.)

2.1.2. Apparatus

The experiment was conducted with custom software written in Python with the PsychoPy libraries (Peirce, 2007). Observers sat approximately 60 cm from a 32° × 26° display, with all subsequent sizes computed based on this distance.

2.1.3 Stimuli

The stimuli consisted of images of various geometric shapes, each

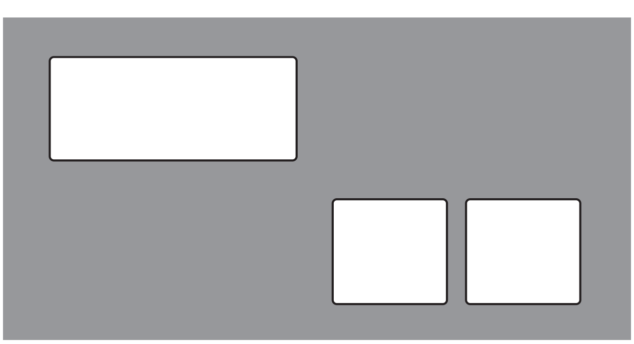

Fig. 1. Depiction of an example display from Experiment 1a. Observers compared a single continuous shape (i.e. the rectangle in the upper left quadrant) with an equivalent set of multiple discrete shapes (i.e. the two rectangles separated by a gap in the lower right). These two stimuli are equally wide (from their leftmost points to their rightmost points), but the continuous entity appears longer.

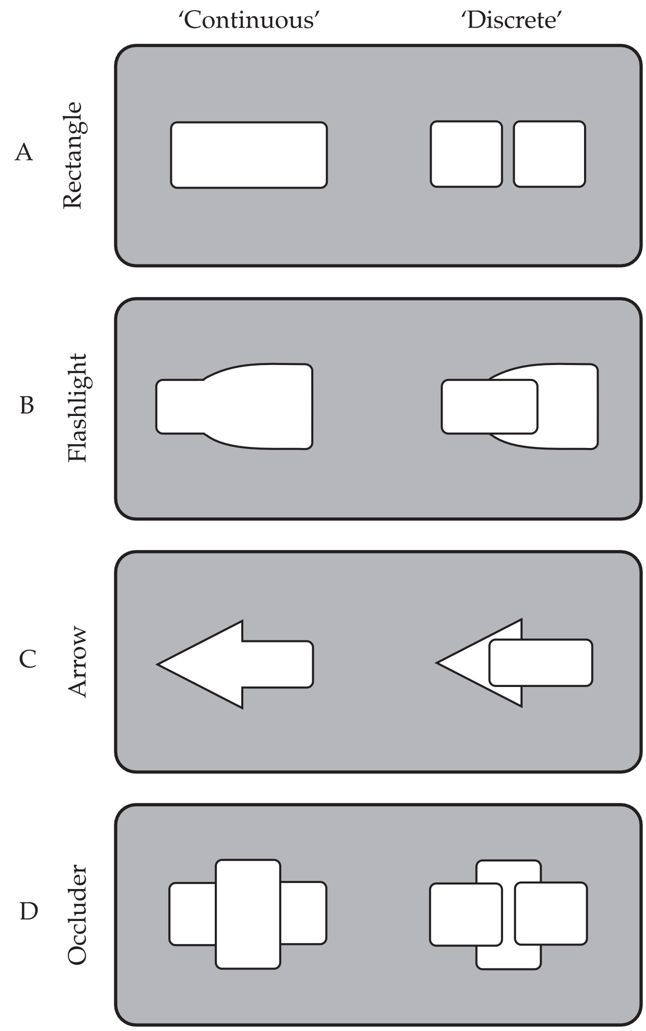

Fig. 2. Depiction of the four shape contrasts tested in Experiments 1a and 1b. In each case, the entities in each row are equally wide.

drawn in white, on a gray background, surrounded by a black 0.08° border. On each trial, one of four possible image pairs (see Fig. 2) was presented, with each image appearing in a diagonally opposite quadrant of the display as in Fig. 1 (counterbalanced across trials, with every image appearing an equal number of times in each quadrant across the experiment as a whole). The center of each image was approximately 10° from the center of the display, with this value horizontally jittered on each trial by a random extent between 0° and 1.3°. Each image pair consisted of one 'continuous' entity and one set of multiple 'discrete' entities (see Fig. 2).

The 'flashlight' stimulus in Fig. 2b was adapted from Cooper and Humphreys (1999), who explored interactions between space and grouping in a way that seems to have presaged the one-is-more illusion. This earlier work was never published, though similar figures were later used in an unrelated study of simultanagnosia (Cooper & Humphreys, 2000). This stimulus, as well as the 'arrow' stimulus in Fig. 2c, also serves an important function in that it is made up of *overlapping* shapes — thus controlling for the possibility that any effects with the other shapes could depend on the presence of a gap between two objects rather than on perceived continuity *per se.*

Each image was always presented with the same height (which ranged from 5.2° as in Fig. 2a to 9.1° as in Fig. 2d), and there were three possible widths: 13.5°, 15°, and 16.5°. The stimuli changed proportionally as the widths changed, as if stretched. E.g., if the stimulus length increased by 10%, then the length of every part, as well as every gap, would increase by 10%. The widths were counterbalanced such that the 'continuous' object was longer on one third of trials (16.5° vs. 15°, or 15° vs. 13.5°), the set of 'discrete' objects was longer on one third of trials (*mutatis mutandis*), and the widths were both 15° on the remaining third of trials.

2.1.4. Procedure

On each trial, observers were simply asked to indicate (by pressing one of two keys, one corresponding to the left image and the other corresponding to the right image) which of the two shapes appeared longer "from the farthest left point to the farthest right point of the image". Both images remained visible until the response was recorded, or until 5 s had elapsed (at which point the display disappeared, no response was possible, and a reminder to respond within 5 s appeared). A blank screen appeared for a randomly chosen interval of 1–2 s after each response, after which the next trial began.

Observers completed two brief practice trials (the results of which were not recorded) followed by 192 test trials (4 image pairs × 4 quadrants × 6 size comparisons × 2 repetitions). Trials were presented in a different random order for each observer. Three times throughout the experiment, at quarter intervals, a message appeared that encouraged observers to rest briefly before continuing.

2.2. Results

The proportion of trials for which observers selected the single 'continuous' entity (as opposed to the set of multiple 'discrete' entities) as longer, when the two were in fact equal in extent (i.e. both 15°), is shown for each image pair in Fig. 3a. Inspection of this figure suggests three salient patterns. First, for the 'rectangle' stimulus, observers selected the single continuous entity nearly 100% of the time. (Of the 10 observers, 8 of them always selected the single continuous rectangle, and the other 2 selected it 15/16 times.) Second, this effect was also present (though slightly weaker) for both the 'flashlight' and 'occluder' stimuli. Finally, observers did not select the continuous 'arrow' significantly more often than chance (though 8/10 observers did so).

These impressions were confirmed by the following analyses. These analyses, and subsequent analyses in all experiments (except those in Experiment 1b, which employed a different design), were conducted on the number of 'continuous' choices selected by each observer (for experiments, like this one, with multiple trials per observer) or the number of observers who reported seeing the 'continuous' entity as longer (for later experiments with a single trial per observer). When the two images were equal in extent (i.e., when we analyze only the 33% of trials in which there was no difference between the stimuli), observers perceived the continuous shape as longer more often than chance for the 'rectangle' (Fig. 2a: $t(9) = 58.50$, $p < .001$, $d = 18.50$), the 'flashlight' (Fig. 2b: $t(9) = 6.09$, $p < .001$, $d = 1.93$), and the 'occluder' (Fig. 2d: $t(9) = 4.29$, $p = .002$, $d = 1.36$) — but not for the 'arrow' (Fig. 2c: $t(9) = 1.62$, $p = .139$, $d = 0.51$). This effect was also remarkably robust across observers: averaged across all image pairs, all 10 observers chose the continuous entity more often than the set of discrete entities (see Fig. 3b). Overall, observers selected the continuous entity as longer 96% of the time when it was in fact longer — but they even selected the continuous entity as longer 40% of the time when it was in fact *shorter*! To confirm that observers were in fact completing the task (and not merely always selecting the continuous entity, say), we also tested whether they were sensitive to the differences in size. In particular, we conducted a repeated measures analysis of variance on the number of 'continuous' choices selected by each observer with three levels (i.e. whether the continuous entity was larger, smaller, or the same as the set of discrete entities). This analysis (collapsed across all stimuli) yielded a main effect of size, $F(2, 18) = 209.57$, $p < .001$, $\eta_p^2 = .980$, indicating that observers were indeed paying attention to the changes in relative size. In other words, observers were most likely to select the continuous entity when it was in fact longer and least likely to select the continuous entity when it was in fact shorter. Complete graphs with data for each shape broken down for each size comparison are included in the supplementary data file.[1]

2.3. Discussion

These results demonstrate the one-is-more illusion. Importantly, the design of this experiment ensured that these results could not be explained by either a failure to attend to spatial extents in the first place (since observers were sensitive to the actual lengths on unequal-extent trials) or by some sort of global response bias (since the illusion occurred to differing degrees across the different shapes). Moreover, the results with the 'occluder' begin to control for possible lower-level differences (beyond objecthood), since these stimuli were equated in terms of both the amount of actual whitespace and the number of contours between the entities' bounding edges. (And accordingly, the effect with this shape rules out any explanation based on the role of intervening contours, *per se* — as has sometimes been suggested for other illusions; e.g. Mikellidou & Thompson, 2014.)

Here, and in subsequent experiments, we often manipulated objecthood in the strongest way we could, by inserting an actual gap between different objects (as in Fig. 2a). That the illusion persisted with at least some cases where this was not true (as in Fig. 2b and d), however, illustrates that connectedness (or the lack thereof) is neither strictly necessary nor sufficient to define objecthood. In fact, previous work in other domains has emphasized that "object-based" effects are rarely all-or-none phenomena, but rather can be strengthened or weakened by multiple independent cues to objecthood (e.g. Feldman, 2007; Marino & Scholl, 2005). We suspect that the same may be true of the one-is-more illusion.

3. Experiment 1b: spatial extent (matching)

Could the one-is-more illusion somehow be specific to the dichotomous which-was-larger method used in Experiment 1a, or might it be a more general phenomenon? To find out, we replicated the effect using the same shapes, but with a new method: observers now simply viewed each shape and then adjusted the height of a different image to match the original image's perceived width.

3.1. Method

This experiment was identical to Experiment 1a except as noted below. 20 new observers participated. This sample size was chosen to be precisely double that of Experiment 1a, given pilot data suggesting that this continuous-adjustment method led to noisier responses.

On each trial, a single one of the eight target images (Fig. 2) was presented vertically-centered and 5° to the left of the display's center. Each of the eight images appeared once in each of the three sizes. On the right side of the display (0.77° right of the center of that half of the screen, and also vertically centered), observers saw (in separate blocks, with the order counterbalanced across observers) either a vertical line (with a stroke width of 0.26°) or two vertically aligned solid dots (each 0.26°).

By making adjustments with the mouse wheel, observers matched the vertical extent of the line/dots on the right side of the display with the perceived width of the image on the left side of the display. The initial height of the line/dots was randomly chosen on each trial to be between 0.5° and 3°. The response tool (whether a line or dots) was

[1] We have also replicated the basic one-is-more effect online using Amazon Mechanical Turk, while also testing other variations of these stimuli. For example, in data not reported here, we have found that this illusion also persists for vertical extent as well as horizontal extent, and that it persists for comparisons of 1 vs. 4 entities as well as 1 vs. 2 entities.

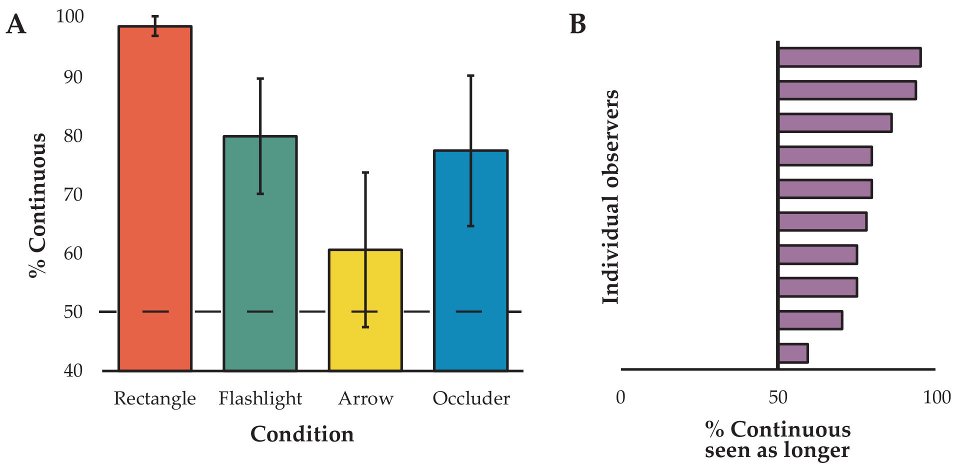

Fig. 3. Results from Experiment 1a: (A) The proportion of 'continuous' entities perceived as longer for each shape (when the continuous and discrete entities were actually equally wide). Error bars depict 95% confidence intervals. The dashed black line represents at-chance performance. (B) The percentage of 'continuous' shapes perceived as longer (when the continuous and discrete entities were actually equally long), for each observer, ordered by effect magnitude.

intentionally oriented vertically in order to make visual matching more challenging. We felt that this would provide the strongest possible evidence of an illusion, at the risk of decreasing the magnitude of any effects. This means, however, that we cannot use these data to assess the magnitude of the one-is-more illusion, as there are known differences in the perception of horizontal and vertical extent (Finger & Spelt, 1947). Observers pressed a key to submit their answers, but could do so only after moving the mouse-wheel up and down at least once. Observers had 12 s to submit each response.

Observers completed two brief practice trials followed by 48 test trials (8 images × 3 sizes × 2 blocks).

3.2. Results and discussion

The mean difference in size estimation for each single 'continuous' entity relative to its counterpart of multiple 'discrete' entities (collapsed across the line/dot blocks) is shown in Fig. 4a. (In the Supplementary Data file we present analyses of the lines vs. dots separately.) Inspection of this figure suggests that the illusion was robust with this paradigm as well, though even more so for the 'arrow' than for the 'flashlight' or the 'occluder'. These impressions were confirmed by the following analyses. First, observers indicated that the single continuous entity was significantly longer than the discrete counterpart with multiple entities for both the 'rectangle' ($t(19) = 2.51$, $p < .021$, $d = 0.56$) and the 'arrow' ($t(19) = 3.48$, $p < .003$, $d = 0.78$), but this effect was absent for the 'flashlight' ($t(19) = 1.49$, $p = .153$, $d = 0.33$) and was only marginal for the 'occluder' ($t(19) = 2.01$, $p = .059$, $d = 0.45$). Collapsed across all shapes, however, the effect was again quite large and robust, $t(19) = 3.75$, $p = .001$, $d = 0.84$. Additionally, as depicted in Fig. 4b, the effect was consistent across observers: 16 of 20 estimated the 'continuous' entity to be longer than its counterpart (binomial test, $p = .012$).

To ensure that observers were attending to the relevant spatial information, we tested whether they were sensitive to the three different image sizes. Indeed, reported lengths of the medium-length images were both greater compared to short images ($t(19) = 14.49$, $p < .001$, $d = 3.24$) and smaller compared to long images ($t(19) = 15.13$, $p < .001$, $d = 3.38$).

These results confirm that the one-is-more illusion generalizes across experimental paradigms — and that it is robust even when no direct comparisons are ever made.

4. Experiment 2a: spatial extent ('Apple core')

If the one-is-more illusion is truly due to *perceived* objecthood, then in an ambiguous figure (that can be seen either as a single shape or as two independent shapes), observers should perceive a difference in widths (across the two possible percepts) *even when the image itself never changes*. Here we tested this in the context of the 'apple core' display depicted in Fig. 5. This figure is ambiguous: it can be seen as either two blue squares partially overlapping a vertically-oriented red rectangle, or as a single horizontally-oriented blue rectangle occluded by a red 'apple core'. Would observers perceive differential spatial extents in these two cases?

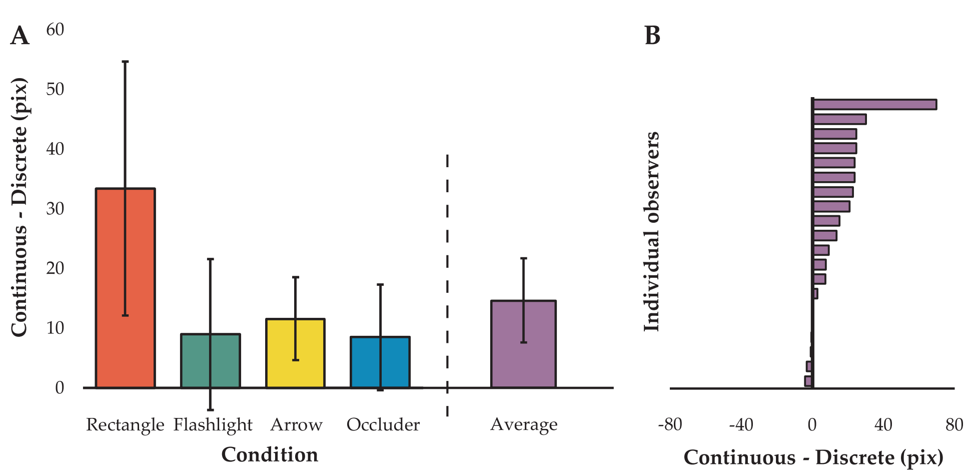

Fig. 4. Results from Experiment 1b: (A) The difference in length estimations between 'continuous' and 'discrete' entities for each shape pair, where error bars represent 95% confidence intervals. (B) The difference in length estimations averaged across all shapes for each observer, ordered by effect magnitude.

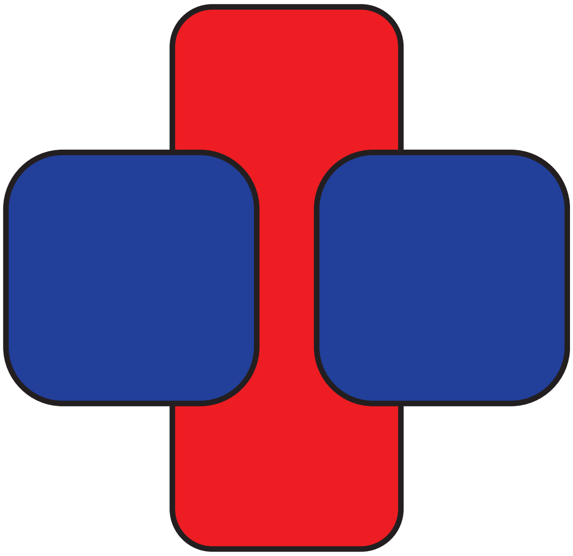

Fig. 5. Depiction of the stimulus used in Experiment 2a. This ambiguous image can be seen either as two blue rectangles that are partially occluding a single red rectangle, or as a single blue rectangle being partially occluded by a single red 'apple core' shape. Observers viewed this single image, and after being familiarized with the two percepts were asked to report which corresponded to a greater perceived width. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

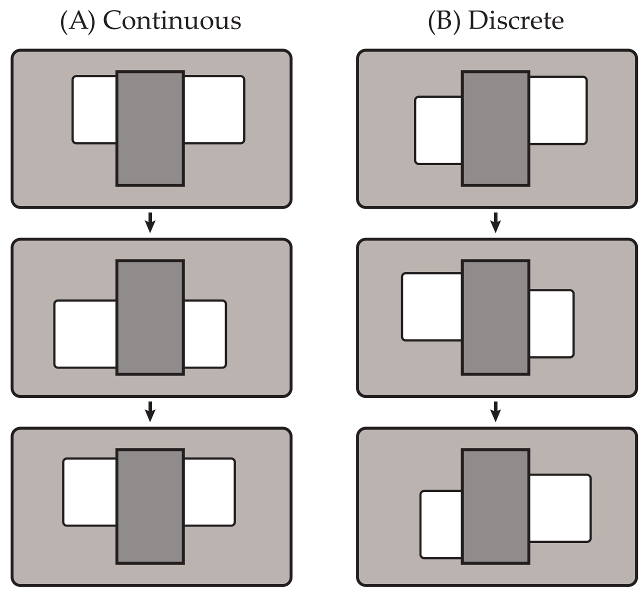

Fig. 6. Depiction of the dynamic stimuli used in Experiment 2b. (A) A single, continuous rectangle that appears to be moving behind an occluder. (B) Local shapes that move independently in the vertical dimension and so appear to be multiple discrete entities. Observers viewed these stimuli in tandem — one on the left side of the screen, and the other on the right — and were simply asked to indicate which looked longer.

4.1. Method

40 new observers participated. This sample size was chosen conservatively before data collection began to be precisely double that of Experiment 1b, based on an expectation that the results would be less robust (since each observer completed only a single trial, compared to 192 in Experiment 1a and 48 in Experiment 1b). Each observer completed a single in-lab trial, while centrally viewing the figure depicted in Fig. 5. This figure had the same width as the 'discrete' occluded stimulus in Experiments 1a and 1b, as in Fig. 2d, but the height was different (matched to the width, 12.8°) and each shape had a 0.10° black border. The two rectangles on either side were blue and the central rectangle was red.

Observers were familiarized with the two possible percepts that could arise from this figure (i.e. two blue rectangles each partially occluding a red rectangle, or a single red 'apple core' shape partially occluding a blue rectangle). They were then asked to verbally indicate (in a forced choice) which percept corresponded to a greater perceived image width.

4.2. Results and discussion

28 of the 40 observers indicated that the image seemed longer with the percept of a single (discrete) blue object behind the red 'apple core' (binomial test, $p = .017$). This experiment demonstrates the one-is-more illusion in an ambiguous figure where all stimulus features are perfectly controlled, such that the only thing changing is perceived objecthood. (On its surface, this may appear to be an example of perception changing as a result of higher-level intention. But in fact we suspect that the relevant causal factor is differential patterns of attention to the shapes. For discussion of why this sort of ambiguous figure doesn't pose a challenge to the 'cognitive impenetrability' of perception, see Pitfall #5 from Firestone & Scholl, 2016.) It was remarkable that the effect persisted in this context, when testing each participant on only a single trial, and when we might expect the illusion to be diminished by the phenomenon of 'amodal shrinkage' (whereby the presence of occlusion perceptually shortens objects even without any change in perceived objecthood; Vezzani, 1999). (It also seems notable that only 70% of observers exhibited the one-is-more effect in this experiment, since this value is clearly lower than the nearly 100% observed in the prior experiments. However, this difference may not reflect anything about the one-is-more illusion itself, given individual differences in the ability and ease with which observers can appreciate both ways of seeing bi-stable images.)

5. Experiment 2b: moving behind occluders

Might the one-is-more illusion in the 'occluder' condition result not from differences in discrete objecthood *per se*, but rather from some other lower-level property (beyond those already controlled for)? To find out, we manipulated perceived objecthood via motion cues, while otherwise equating the stimuli. In particular, we contrasted a case wherein two shapes were seen as a single occluded rectangle based on their common motion (Fig. 6a) with a case in which the identical two shapes were seen as separate entities based on their independent motions (Fig. 6b). This stimulus is difficult to depict in static images, but a dynamic animation can be viewed online at http://perception.yale.edu/one-is-more/.

5.1. Method

40 new observers participated. This sample size was chosen before data collection began to be identical to that of Experiment 2a. The experiment was conducted in a local library on a laptop computer.

In describing these stimuli there is some potential for terminological confusion, since there are three sorts of 'rectangles' being used: the occluder, the moving (unoccluded) shapes, and the larger moving shape that may complete behind the occluder. To avoid this ambiguity, (a) we will always use "stationary rectangle(s)" to refer to either of the two central unmoving rectangles (that may function as occluders); (b) we will always use "local shape(s)" to refer to any of the four smaller rectangles visible on either side of a stationary rectangle, without any completion; and (c) we will always use "completed rectangle" to refer to the larger moving rectangle (made up of two local shapes) that may be seen to complete behind the stationary rectangle. Thus, for example, we can summarize Fig. 6a by noting that the two local shapes are perceptually joined behind the stationary rectangle to form a completed rectangle.

The display was divided into four quadrants, but only the top-left and bottom-right quadrants contained images. The top-left quadrant and the bottom-right quadrant each contained a centered stationary gray rectangle (vertically oriented, 7.7° × 12.8°). Next to each stationary occluder were two local shapes that if aligned would appear to form a single completed rectangle behind an occluder. (Each local shape was white with a black border, with a height and width identical to the rectangle in Experiment 1a, and the white regions always ended at the adjacent occluding boundary). The local shapes in the upper-left quadrant of the screen moved in tandem, such that their common motion gave rise to the percept that the two shapes were part of a larger completed rectangle. The local shapes in the bottom-right quadrant of the screen moved asynchronously, giving rise to the percept that they were two separate entities moving next to the stationary rectangle. (We included horizontal motion in addition to vertical motion in order to have as much common motion as possible, so as to reinforce the difference between the continuous and the discrete stimuli. In addition, the horizontal motion may have helped to make our key manipulation less obvious.)

In the top-left quadrant of the display, the left local shape could initially appear with its leftmost edge between 4.40° and 7.99° to the left of the stationary rectangle's left edge, and the horizontal position of the right local shape was always matched to that of the left local shape such that both of them together spanned exactly 15°. Both local shapes appeared in the same vertical position such that their upper edges were between 0.13° and 5.25° below the stationary rectangle's upper edge (with each of the initial positions randomly chosen independently for each trial, for each observer, within these constraints).

The local shapes always moved 2.2°/s, initially in a (matched) random direction on the left, and in independent random directions on the right. The horizontal and vertical components of each motion vector changed independently whenever the next frame of motion would move a local shape beyond its possible range of initial positions. And, independent of those changes, there was also a 50% chance that a local shape would reverse either its horizontal or vertical direction (or both, independently) every 2 s (where those actual moments of potential random change were staggered by 1 s across the two local shapes in each pair). Consequently, the local shapes changed their motion directions approximately once every 1.5 s.

To prevent observers from responding too quickly (and to give them time to experience the common vs. independent motion), they could not respond until a horizontal green line (with a stroke of 0.10°, spanning the width of the display) appeared, centered vertically (such that it appeared just below the occluder on the left side of the display, and just above the occluder on the right side of the display). This line appeared whenever the centers of the two independent local shapes (in the bottom-right quadrant of the display) moved 2° apart in the vertical dimension (which on average occurred after 3.46 s), or whenever 10 s had elapsed — whichever came first. (In practice, this meant that the green line appeared on average after 4.56 s.) Observers were simply asked to indicate (by pressing one of two keys, one corresponding to the left image and the other corresponding to the right image) which of the two shapes appeared longer "from the farthest left point to the farthest right point of the image". Each observer completed six test trials, with no time pressure to respond.

5.2. Results and discussion

Observers selected the shapes that appeared to be a single occluded rectangle as the wider stimulus on 70% of trials, $t(39) = 6.11$, $p < .001$, $d = 0.97$. Only 3 of the 40 observers chose the independently-moving shapes as longer on a majority of trials. Given that the continuous vs. discrete contrast in this experiment was implemented via (common vs. independent) motion alone, we conclude that the one-is-more illusion results from a difference in perceived objecthood, *per se*, as opposed to a difference in the number of spatial gaps or the overall amount of whitespace in an image.

6. Experiment 2c: fixed-depth images

Is it possible that differences in perceived *depth* caused by occlusion (as in Experiments 2a and 2b) could somehow explain the one-is-more illusion? This might be the case if, for example, the occluded shapes are seen as relatively farther away, and thus wider due to size constancy. We were initially rather uncertain about this possibility, since we have already observed the one-is-more illusion in a case wherein perceived depth from occlusion should have been equated (i.e. in Experiment 2b; cf. Fig. 6). Nevertheless, we also decided to test this empirically by directly manipulating stereoscopic depth.

6.1. Method

This experiment was identical to Experiment 1 except as noted here. 80 observers participated (with this sample size chosen before data collection began in order to effectively match those of Experiments 2a and 2b, which each had 40 observers per condition). Observers viewed only a single stimulus (a version of the 'occluded rectangle' display) and completed only a single trial. Critically, these images were rendered (while the observers wore stereogoggles) so as to have precise stereoscopic depth information. For half of the observers, the occluded rectangle was rendered to be exactly the same perceived depth as the two discrete rectangles; for the other half, it was rendered to be perceived as exactly twice as far away (see Fig. 7). Four observers were removed and replaced based on a post-test when they were unable to report which of two rendered spheres appeared to be farther away (when one was rendered so as to be perceived as twice as far away as the other).

6.2. Results and discussion

When the occluder was perceived to lie in a closer depth plane than the other shapes, 38 of 40 observers perceived the single continuous

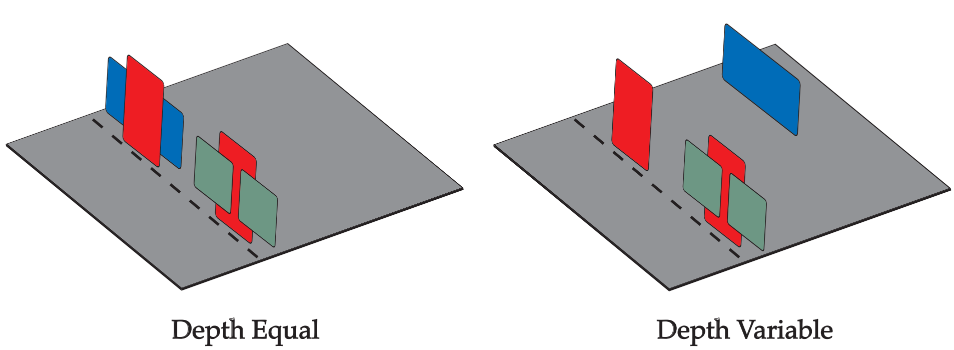

Fig. 7. Caricatured depictions of the two conditions in Experiment 2c. The left panel depicts the depth-equated condition, and the right panel depicts the depth-variable condition. The size of the blue rectangle in the depth-variable condition was adjusted so that the retinal size of the blue rectangles across conditions was equated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

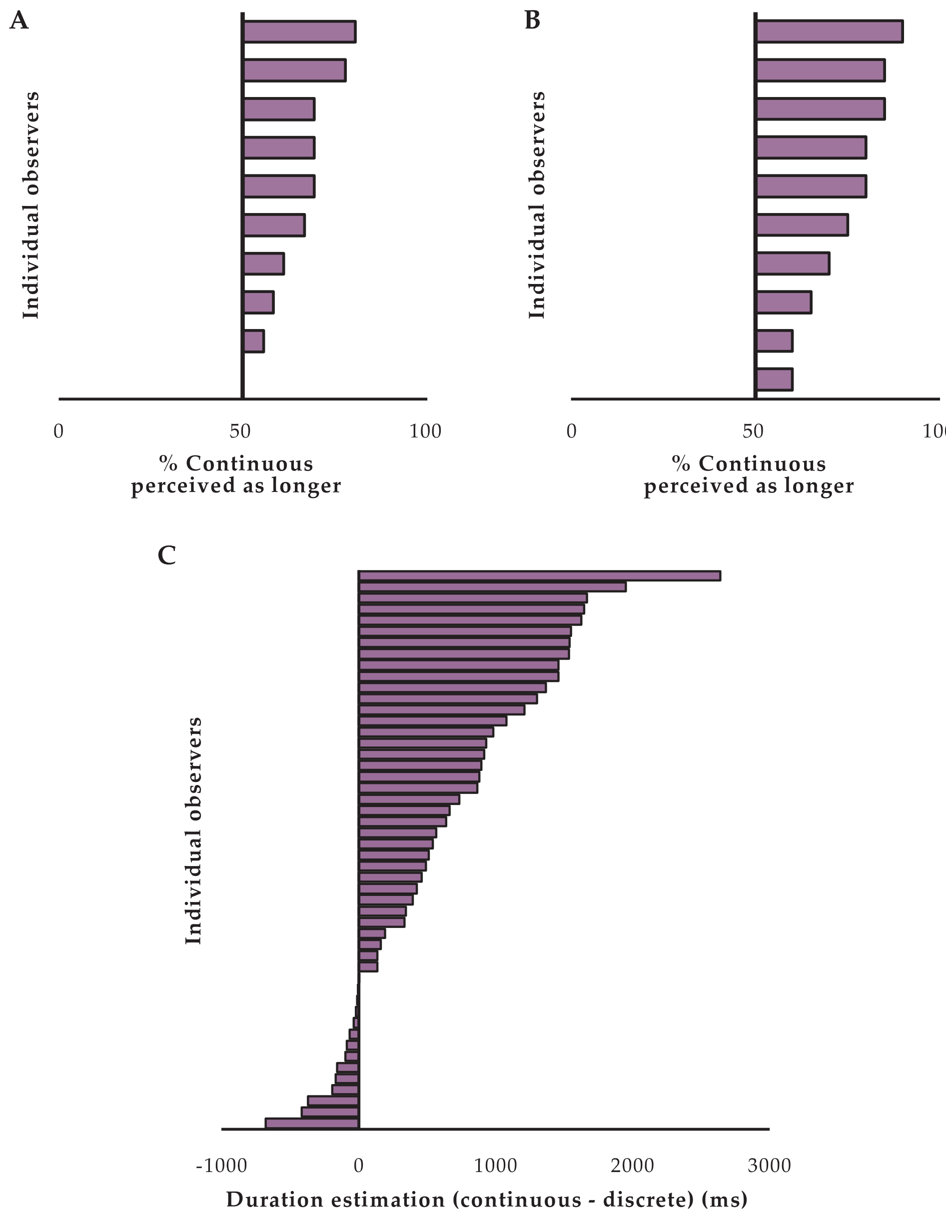

Fig. 8. The percentage of 'continuous' shapes perceived as (temporally) longer, for each observer, ordered by effect magnitude in (A) Experiment 3a (when the continuous and discrete entities were actually equally long), and (B) Experiment 4. Also, (C) the average difference (in ms) of all continuous and discrete duration estimations for each observer in Experiment 3b.

rectangle as longer ($p < .001$). And when the occluder was perceived to lie in the *same* depth plane as the other shapes, 34 of 40 observers still indicated that the single continuous rectangle looked longer ($p < .001$). This confirms that the one-is-more illusion cannot be explained by appeal to differential perceived depth. (This did not surprise us, since while the T-junctions in the original 2D 'occluder' condition did indeed give rise to a perceived depth *ordering*, they did so without any great difference in perceived disparity — appearing as if the display involved one piece of paper lying just atop another.)

7. Experiment 3a: temporal extent (comparison)

Is the one-is-more illusion specific to visual space? Rather than viewing visual objects and assessing their spatial extents, observers compared the perceived *temporal* extents of continuous individual sounds (i.e. a single extended tone) and equated sets of discrete sounds (e.g. two independent tones separated by a brief silence). Demonstrations of such stimuli can be heard at http://perception.yale.edu/one-is-more/.

7.1. Method

This experiment was identical to Experiment 1a except as noted here. 10 new observers participated, with this sample size chosen to match that of Experiment 1a.

On each trial, observers listened using headphones to both a single continuous tone (131 Hz, as presented by the SoundPyo library used with PsychoPy, at a volume chosen to be comfortable by each observer) and a set of multiple discrete tones (each of the same character, separated by a period of silence). The start-to-finish durations of the stimuli (regardless of whether a tone was interrupted by a silent gap) came in three broad categories: short (~2.25 s), medium (~4.5 s), and long (~9s). Within each category, there were three possible stimulus durations (2.00 s, 2.25 s, 2.50 s; 4.00 s, 4.50 s, 5.00 s; 8.00 s, 9.00 s, 10.00 s). The relative durations were counterbalanced such that on one-third of trials, the single 'continuous' tone was longer, on another one-third the set of multiple 'discrete' tones was longer, and on the remaining one-third the two were equal. The silent gap on each trial always corresponded to 1/9 the total duration of that stimulus.

On each trial, observers heard a voice say "one", followed 1 s later by the presentation of the first stimulus; 1 s later, the same voice said "two", followed 1 s later by the presentation of the second stimulus. Observers were instructed to press one key if the first stimulus seemed to last longer, and a different key if the second stimulus seemed to last longer. The instructions emphasized that they were comparing the total stimulus durations, including the silences.

Observers completed two brief practice trials, followed by 36 test trials (3 duration categories [short, medium, long] × 3 particular durations within each category × 2 orders [gap first, gap second] × 2 repetitions).

7.2. Results and discussion

A repeated-measures analysis of variance revealed no differences in the magnitude of the effect (i.e., the propensity to indicate that the continuous entity seemed longer) across the three broad duration categories ($F(2,18) = 1.43$, $p = .27$, $\eta_p^2 = .137$), and so subsequent analyses are collapsed across these levels. Observers were generally able to distinguish the relative durations of the tones: for the trials with unequal durations, observers chose the longer tone 67% of the time, $t(9) = 4.49$, $p = .002$, $d = 1.42$. At the same time, and consistent with what was observed in the domain of space, observers chose the single 'continuous' tone as longer on 66% of equal-duration trials, which was significantly more often than chance, $t(9) = 5.20$, $p < .001$, $d = 1.65$. Critically, this result cannot be explained by appeal to the difference in amount of actual auditory stimulation itself (i.e. excluding the silence). For the 33% of the trials in which the set of discrete entities was longer in duration, the set of discrete entities actually contained the same 'amount' of tone as its continuous counterpart. E.g., if the total duration of the continuous entity was 2.00 s and the total duration of the set of discrete entities was 2.25 s, 0.25 of the latter duration was silence. Thus, the cumulative duration of the tone is equal in both cases. Even so, the effect held: if we analyze only those trials where duration was equated, observers still perceived the continuous tone as being longer in duration, $t(9) = 4.58$, $p = .001$, $d = 1.45$.

This experiment demonstrates that the one-is-more illusion extends beyond both space and vision, and is just as robust in time and audition: indeed, as depicted in Fig. 8a, not a single observer perceived the sets of multiple discrete tones as lasting longer on average than the single continuous tones (when they were in fact equated).

8. Experiment 3b: temporal extent (matching)

Experiment 3a demonstrates the powerful tendency to perceive single continuous auditory stimuli as lasting longer than equivalent stimuli with multiple discrete tones. However, observers in the prior experiment were always making an explicit selection between the two. Would the same be true if observers simply reproduced the durations themselves?

8.1. Method

This experiment was identical to Experiment 3a except as noted here. 50 new observers from Amazon Mechanical Turk participated. Expecting that effects in this experiment might be subtle (due to the changes in the paradigm and the testing platform), the sample size was chosen to be substantially greater than that of Experiment 3a (arbitrarily quintupled). (However, as described below, it turns out that we were quite incorrect in thinking these effects would be subtle.)

Observers were instructed to listen to an auditory stimulus and then recreate its duration. They did so by holding down the spacebar on their keyboard. While the tone played, the text 'The sound is now playing…' appeared in black text in the center of the screen. After the tone finished playing, the text 'Now recreate the duration by holding down the spacebar!' appeared. While they held down the spacebar, that text on the screen became red (to indicate that a response was being recorded). When they released the spacebar, the experiment would move on to the next trial. Observers completed 2 practice trials followed by 12 test trials (3 durations [2500 ms, 3500 ms, and 4500 ms] × 2 conditions [continuous, discrete] × 2 repetitions).

8.2. Results and discussion

The results of this experiment are depicted in Fig. 8c in terms of the degree to which each observer perceived the single continuous tone as lasting longer than the set of multiple discrete tones (with the observers ordered in the graph by the magnitude of this difference). As is evident from the figure, 37 of the 50 observers perceived a single continuous tone as lasting longer than its equivalent set of multiple discrete tones. Collapsed across durations, observers perceived the single continuous tones to be 640 ms longer, $t(49) = 6.39$, $p < .001$, $d = 0.89$. This design also allows us to quantify the magnitude of the illusion: observers perceived the single continuous tone as lasting 32% longer, 30% longer, and 31% longer for the 2500 ms, 3500 ms, and 4500 ms durations, respectively. In other words, the one-is-more illusion here is perhaps *even stronger* than was indicated by the previous experiments. Furthermore, this design rules out the possibility that the prior results can be explained by some sort of response bias.

9. Experiment 4: temporal extent (occlusion)

In Experiments 1a and 1b, we used the 'occluder' stimulus (Fig. 2d) to equate the continuous vs. discrete stimuli for amount of actual whitespace. In a similar vein, this experiment used auditory occlusion (a static burst, adapted from Bregman, 1994; see http://perception.yale.edu/one-is-more/) to further equate the temporally continuous vs. discrete stimuli for amount of actual auditory stimulation (i.e., the total duration for which a tone (as opposed to static or silence) was playing).

9.1. Method

This experiment was identical to Experiment 3a except as noted below. 10 new observers participated, with this sample size chosen to match that of Experiment 3a. Rather than comparing tones separated by a silent gap to continuous tones, observers compared tones separated by a silent gap to identical tones separated instead by an equally long burst of static (a manipulation which creates a vivid impression — analogous to visual occlusion — that a single tone continued during the static; Bregman, 1994). There were three possible stimulus durations (800 ms, 1000 ms, 1200 ms), and the periods of static/silence were always 100 ms regardless of the stimulus duration. Observers completed two brief practice trials followed by 20 test trials. 4 of the test trials had equal (1000 ms) durations (2 orders [static first, static second] x 2 repetitions), and 16 had unequal durations (2 duration comparisons [800 ms vs. 1000 ms, 1000 ms vs. 1200 ms] × 2 duration condition assignments [shorter duration has static, longer duration has static] × 2 orders [static first, static second] × 2 repetitions).

9.2. Results and discussion

Observers were generally able to distinguish the relative durations of the tones: for trials comparing unequal durations, observers chose the longer tone on 73% of trials, $t(9) = 6.41$, $p < .001$, $d = 2.03$. Overall, observers perceived the single 'continuous' tone (i.e. the sound that seemed to continue during a burst of static) as longer on 75% of trials — significantly more often than expected by chance, $t(9) = 7.32$, $p < .001$, $d = 2.32$. This effect persisted even when analyzing only the four equal-duration trials, $t(9) = 4.81$, $p < .001$, $d = 1.52$. And once again, this effect was exceptionally reliable: as depicted in Fig. 8b, 100% of observers perceived the continuous tones (with static bursts) as lasting longer than the sets of multiple discrete tones (separated by silent gaps).

Analogous to the visuo-spatial examples in the earlier experiments, these results demonstrate that the 'audio-temporal' one-is-more illusion is due to perceived auditory objecthood *per se*, rather than to the actual amount of auditory stimulation.

10. General discussion

The eight experiments reported here collectively demonstrate the one-is-more illusion: observers (mis)perceive single continuous entities as more extended than equivalent sets of multiple discrete entities. This was true in both space (Experiments 1 and 2) and time (Experiments 3 and 4), with both dichotomous judgments (e.g. Experiments 1a, 2a-c, 3a, and 4) and matching (Experiments 1b and 3b), and even while carefully controlling for various lower-level factors, including the amount of actual (visuo-spatial or 'audio-temporal') stimulation (Experiments 2a, 2b, 2c, and 4). Moreover, the illusion is powerful enough to make perceived extent change right in front of your eyes, when switching between two percepts of the relevant kind of ambiguous figure (Experiment 2a; Fig. 5).

Though these effects were remarkably robust across both paradigms and observers (often with over 90% of observers demonstrating such effects), there was some variability across experiments. Most notably, in Experiments 2a and 3b, only 70–75% of observers demonstrated the illusion. However, it seems likely that this could be due to the particular methodologies of these studies — since the former required observers to appreciate a subtle bi-stable percept, and the latter involved a mere 12 trials in an online sample. Excluding these two experiments, over 90% of observers consistently exhibited a one-is-more effect, even across the 7+ unique paradigms used here.

10.1. Related phenomena

The one-is-more illusion seems distinct in interesting ways from other illusions of spatial and temporal extent. In the Oppel-Kundt (O-K) illusion (Kundt, 1863), for example, additional vertical bars placed between two parallel vertical bars cause the entire stimulus to appear longer. And this has a temporal analogue in the 'filled-duration illusion' (Thomas & Brown, 1974), in which additional tones placed between two temporally-distant tones cause the entire sequence to seem to last longer.

Yet these examples both seem orthogonal to the one-is-more illusion. First, their underlying questions may differ: whereas the present work contrasts singular continuous entities with sets of multiple discrete entities — contrasting (an indivisible) 'one' with 'more than one' — it is unclear how these other illusions should be characterized. The O-K illusion has traditionally been studied with textures of 7–14 lines — a contrast between 'some' and 'some more' (e.g. Robinson, 1972). The illusion does eventually break down after the addition of many lines, but this may be at the point where observers stop perceiving the stimulus in terms of discrete lines, and instead simply perceive it as a single dense texture (something that must happen eventually).

At least one O-K study also explored the perceived extents of lines that were or were not bisected by a tick mark (Mikellidou & Thompson, 2014). Yet even this work is ambiguous, since such stimuli also had additional ticks at either end — making it ambiguous whether the underlying contrast was between 0 and 1 or between 2 and 3. (We carefully constructed our stimuli without such ambiguity.) In any case, the *results* of these experiments draw an even clearer distinction: adding more entities in these other illusions nearly always makes the stimulus seem longer, whereas adding more entities in the one-is-more illusion makes the stimulus seem shorter.

The one-is-more illusion may be more related to 'object-based warping', in which the perceived distance between two dots appears greater when the dots are superimposed on a single object, rather than two objects, or nothing at all (Vickery & Chun, 2010). Most of the contrasts in object-based warping were between dots-on-an-object vs. dots-not-on-an-object (including dots in otherwise-empty space, or dots situated between two objects). In a way that seems consistent with the one-is-more illusion, dots-on-an-object are also seen to be further apart than are dots-on-distinct-objects. Accordingly, each phenomenon may help to illuminate the other. The phenomenon in this earlier work was specific to the dots; these authors never asked whether the continuous objects *themselves* ever seemed longer (and indeed, no such effect appeared in the paper's figures — perhaps because the relevant stimuli were always perfectly spatially aligned). But the one-is-more illusion in this context suggests that what was being 'warped' in the first place was the *objects*, rather than just the dots themselves. And by the same token, object-based warping suggests that perhaps the one-is-more illusion arises not simply from the two most extreme parts of a continuous entity being perceived as more distant, but from the entirety of the continuous object being perceptually 'stretched' relative to sets of multiple objects.

A final effect that may be related to the one-is-more illusion is 'amodal shrinkage' (e.g. Vezzani, 1999). As mentioned briefly in the discussion of Experiment 2a, this is the phenomenon whereby an occluded image (e.g. a horizontal rectangle behind a vertical rectangle) is perceived as being *shorter* in extent than its non-occluded counterpart (e.g. a horizontal rectangle with nothing in front of it). On the surface these two effects may seem entirely orthogonal: the one-is-more illusion is all and only about the continuous/discrete distinction, whereas the entire point of amodal completion is that the two parts of an occluded shape are completed into a single (continuous) whole behind the occluder. However, this ultimate continuous percept of occlusion may still mask the possibility that at earlier levels of visual processing the two parts of the rectangle are perceived as distinct (cf. Rauschenberger & Yantis, 2001). If so, then perhaps a weak form of the one-is-more illusion could explain why amodal shrinkage occurs? Indeed, though our experiments were not designed to assess this relationship, it was consistently the case that occluded rectangles were seen as (a) longer in extent than discrete rectangles, but (b) shorter in extent than non-occluded, continuous rectangles.

10.2. Conclusions: phenomenological consequences of continuous vs. discrete representations

Although the contrast between continuous vs. discrete representations has been foundational in the study of perception (including in studies of object-based attention and visual working memory), it has rarely if ever been something that could be directly phenomenologically appreciated. In contrast, the one-is-more illusion shows how continuous entities are not only treated differently by mechanisms of attention and memory, but are also *seen* (and *heard!*) in different ways — resulting in substantial distortions of space and time alike.

11. Author note

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12. Author contributions

S.R. Yousif and B.J. Scholl designed the research and wrote the manuscript. S.R. Yousif conducted the experiments and analyzed the data with input from B.J. Scholl.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2018.10.002.

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