COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 46 (2021) e13073

ISSN: 1551-6709 online
DOI: 10.1111/cogs.13073

A Holey Perspective on Venn Diagrams

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Received 26 February 2021; received in revised form 26 October 2021; accepted 29 October 2021

Abstract

When interpreting the meanings of visual features in information visualizations, observers have expectations about how visual features map onto concepts (*inferred mappings*.) In this study, we examined whether aspects of inferred mappings that have been previously identified for colormap data visualizations generalize to a different type of visualization, Venn diagrams. Venn diagrams offer an interesting test case because empirical evidence about the nature of inferred mappings for colormaps suggests that established conventions for Venn diagrams are counterintuitive. Venn diagrams represent classes using overlapping circles and express logical relationships between those classes by shading out regions to encode the concept of non-existence, or none. We propose that people do not simply expect shading to signify *non*-existence, but rather they expect regions that appear as holes to signify non-existence (the *hole hypothesis*.) The appearance of a hole depends on perceptual properties in the diagram in relation to its background. Across three experiments, results supported the hole hypothesis, underscoring the importance of configural processing for interpreting the meanings of visual features in information visualizations.

Keywords: Visual reasoning; Information visualization; Configural processing; Perceptual organization; Diagrams

1. Introduction

Information visualizations have the potential to present complex information in natural and accessible formats, which makes them useful for visual communication (Larkin & Simon,

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1987; Giardino & Greenberg, 2015). For example, visualizations are used to illustrate metamorphosis in scientific diagrams (Menendez, Rosengren, & Alibali, 2020), linear equations in mathematical diagrams (Carter, 2018; Nagashima et al., 2020), and universal and existential generalizations in logic diagrams (Moktefi & Shin, 2013; Shin, 1994). To understand the meaning encoded in visualizations like these, observers must be able to form mental representations of abstract concepts on the basis of concrete visual features perceived in visualizations (Hegarty & Just, 1993; Paas, Renkl, & Sweller, 2003; Shah & Hoeffner, 2002).

In some cases, text, legends, or labels specify *encoded mappings*: "rules" of how to interpret the meaning of visual features in visualizations. However, observers have expectations, called *inferred mappings*, about how visual features should map onto concepts.[1] These expectations may or may not align with encoded mappings in the visualization design. Visualizations that violate those expectations are more difficult to interpret, even in the presence of clear legends or labels, because they require additional processing to resolve conflicts between expectations and observations (Kosslyn, 1996; Lin, Fortuna, Kulkarni, Stone, & Heer, 2013; Schloss, Gramazio, Silverman, Parker, & Wang, 2019; Schloss, Lessard, Walmsley, & Foley, 2018; Tversky, 2011; Tversky, Morrison, & Betrancourt, 2002). Thus, for visualizations to present complex information in natural and accessible formats, it is necessary to understand the nature of people's inferred mappings.

The present study is part of an effort to understand the perceptual factors that contribute to people's inferred mappings for information visualizations (Cuff, 1973; McGranaghan, 1989, Tversky 2011; Schloss et al., 2018, 2019; Sibrel, Rathore, Lessard, & Schloss, 2020). Much of this work has been conducted using colormap data visualizations, in which gradations of color correspond to gradations of quantity (e.g., weather maps, neuroimaging brain maps, epidemiological maps).

Two key biases have been identified that influence inferred mappings for colormaps: the *dark-is-more bias* and the *opaque-is-more bias*. In the dark-is-more bias, people infer that the darker regions map to larger quantities (Cuff, 1973; McGranaghan, 1989; Schloss et al., 2019; Sibrel et al., 2020). In the opaque-is-more bias, people infer that the regions appearing more opaque (less transparent or "see-through") map to larger quantities (Schloss et al., 2019). This bias leads to inferences that darker colors map to larger quantities when visualizations are presented on light backgrounds (consistent with the dark-is-more bias), whereas lighter colors map to larger quantities when presented on dark backgrounds (conflicting with the dark-is-more bias). Under such conflicts, the opaque-is-more bias cancels or even overrides the dark-is-more bias.

One may suppose that these effects of the background were merely due to lightness contrast, such that observers inferred regions having greater lightness contrast with the background map to larger quantities. However, background lightness did not affect inferred mappings when colormaps did not appear to vary in opacity—the dark-is-more bias prevailed on both dark *and* light backgrounds (Schloss et al., 2019). The effect of background lightness increased with increased perceptual evidence that colormaps appeared to vary in opacity.

These prior results indicate that inferred mappings do not merely depend on local features of elements in visualizations, such as lightness contrast across edges, but also depend on configural properties[2] such as the relationships between surfaces and background regions in the whole scene.

In the present study, we examined whether aspects of inferred mappings previously identified for colormaps extend to a qualitatively different type of visualization for expressing logical propositions: Venn diagrams. Using a Venn diagram, one can encode, for example, that nothing is both a dog and a cat by drawing two partially overlapping circles—one for the set of dogs and one for the set of cats—and marking the intersection of those circles in such a way as to express that nothing exists that is a member of both of the corresponding sets. Venn diagrams offer a useful test case of whether inferred mappings generalize across different types of visualizations. In the initial formulation, Venn (1881) established a convention that conflicts with inferred mappings established for colormaps.

Venn (1881) specified that darker, shaded-out regions of the diagram encode that there is *nothing* in the corresponding set (i.e., that the regions depict an *empty* or *null* set), stating:

> What we do then, is to ascertain what combinations or classes are negative by any given proposition, and proceed to put some kind of mark against these in the diagram. For this purpose the most effective means is just to shade them out. (cited in Shin, 1994, p. 18)

This convention to shade out regions to encode non-existence has been upheld in subsequent iterations of logical diagrams based on Venn's system (Peirce, 1933; Shin, 1994). Shading out regions to express the emptiness of the corresponding class may have seemed like a natural choice when drawing by hand, as a sort of "crossing out" action. However, that does not mean that when viewing Venn diagrams people will infer that shading means non-existence.

In comparing Venn diagrams to colormaps, the concepts of "no/none/nothing" may be considered the least element on a scale of quantifier concepts that include "all/every," "many/more/most," "some/any," and "no/none/nothing" (Barwise & Cooper, 1981; de Carvalho, Reboul, der Henst, Cheylus, & Nazir, 2016). If so, then mapping "nothing" to the shaded, darker regions of the diagram conflict with the dark-is-more and opaque-is-more biases (assuming a white background as typical for printed pages). This potentially counterintuitive encoding implies that observers may infer the opposite meaning of what was intended by the Venn system.

In the following sections, we first explain the Venn diagram system and how it is used to encode logical propositions. We then propose a new hypothesis concerning inferred mappings for Venn diagrams, called the *hole hypothesis*. Finally, we explain the general paradigm used to test this hypothesis used in Experiments 1–3 of the present study.

1.1. Venn diagram system

Venn diagrams were created by Venn (1881) as a method to visually represent logical propositions. Venn diagrams encode information about the intersections of different classes of entities. They are constructed in two stages. The first stage is creating a *primary diagram*, which consists of two or more circles positioned such that each circle overlaps with every

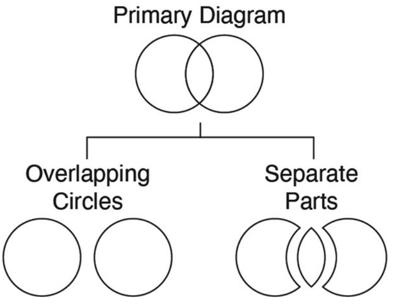

Fig 1. A primary diagram in the Venn diagram system using two overlapping circles. From a perceptual perspective, this primary diagram is likely perceived as consisting of two whole circles that overlap (Kanizsa, 1979). Within the Venn system, the region where the circles overlap has its own significance, designating the (potentially empty) class of entities that belong jointly to the classes designated by each circle.

other circle (Fig. 1). In a given diagram, each circle signifies a (potentially empty) class of entities—such as the class of alien animals on a given planet and the class of furry alien animals.[3] The regions in which multiple circles overlap signify the (potentially empty) intersection of the corresponding classes (e.g., the class of individuals that are both alien animals on the planet and furry). However, primary diagrams do not in themselves encode any logical relationships between these classes.

The second stage turns the primary diagram into diagrams that express logical relationships by introducing visual features that signify the emptiness of a class. When such a visual feature (e.g., shading) is added to a region of the diagram, this feature signifies that nothing exists in the class corresponding to the region. For succinctness, hereafter we will refer to this visual feature as signifying "non-existence." Venn represented non-existence, or the emptiness of a represented class, by shading in the corresponding region of the diagram (Fig. 2). For example, one can depict that there is no intersection between the class of furry alien animals and the class of alien animals on planet Sparl by shading the region in which the circles designating those classes overlap (see Fig. 2c). Note that the absence of shading does not have any significance of its own within the Venn system—the absence of shading in a region does not indicate that the corresponding class contains members.

The Venn system requires that each bounded region in the diagram code information (e.g., the left, middle, and right regions in Fig. 1). This may seem unintuitive for a couple of reasons. First, in Fig. 1, observers are likely to perceive two overlapping circles rather than three distinct regions (Kanizsa, 1979). To treat the region of overlap as a separately meaningful part of the diagram requires overriding natural perceptual organization. Second, Venn diagrams are understood (and sometimes misunderstood) colloquially as overlapping circles where the regions of overlap represent characteristic similarities between the classes represented by the circles. For an example of a colloquial use, imagine a teacher using a Venn diagram to show their students similarities and differences between bananas and lemons. The teacher tells their students that the left circle represents bananas and the right circle represents lemons. The students' task is to write the unique characteristics of lemons (i.e., sour) and bananas (i.e.,

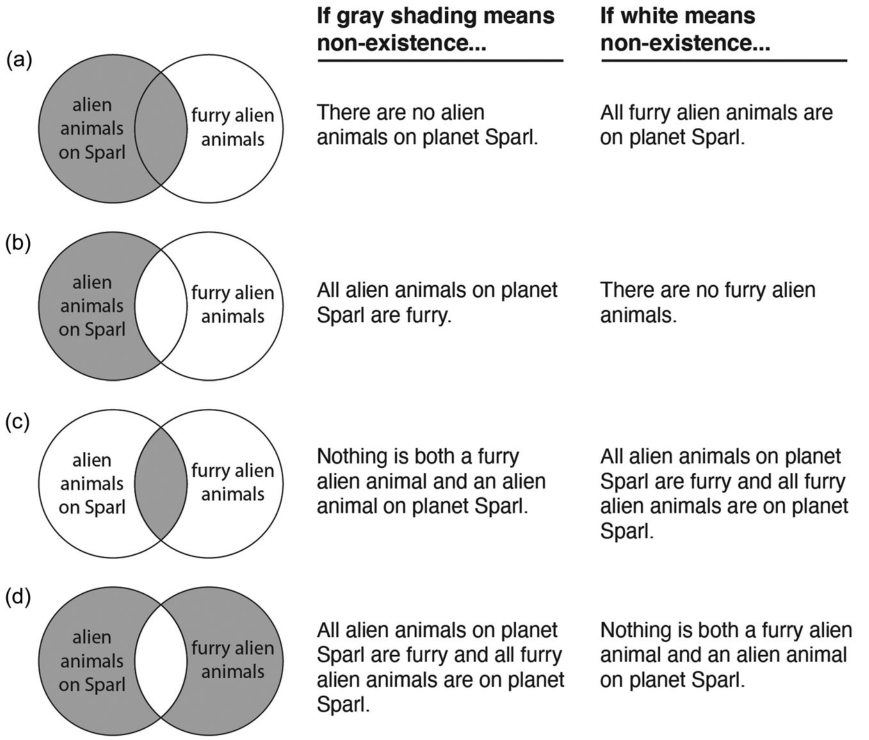

Fig 2. Venn diagrams that express different logical statements concerning two classes, alien animals on Sparl and furry alien animals. The statement immediately to the right of each diagram corresponds to the encoded proposition if non-existence is represented by gray, shaded, regions (as in Venn's original system). The statement on the far right corresponds to the encoded proposition if non-existence is represented by the white regions.

sweet) in the non-overlapping regions, and the shared characteristics of both bananas and lemons in the overlapping region (i.e., yellow, fruit). This colloquial use is not aligned with the Venn system.

1.2. *Inferred mappings for Venn diagrams?*

We now return to the question of what perceptual factors influence inferred mappings for Venn diagrams and introduce the *hole hypothesis* that motivated the present study. Generally, holes are interior regions of surfaces that do not contain matter (Palmer, 1999). Percepts of holes in surfaces arise when enclosed regions of surfaces appear empty, revealing the background through their apertures (Bertamini, 2006; Nelson & Palmer, 2001; Palmer, 1999; Peterson, 2003). Several factors influence whether inner regions of enclosed contours appear as holes, including when inner and outer regions group together (e.g., grouping by color similarity, texture, similarity, common fate, and synchrony) (Nelson & Palmer, 2001). Fig. 3a (top) shows a classic example (adapted from Nelson & Palmer, 2001) in which color similarity leads to the percept of a hole. By virtue of the inner and outer regions sharing the

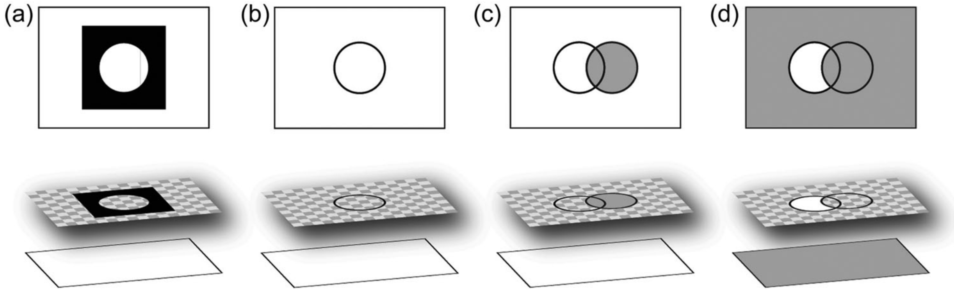

Fig 3. Illustration of how Venn diagrams can be considered as having apparent holes. (a) A classic configuration that supports the percept of a hole (top) (Nelson & Palmer, 2001) with a diagram (bottom) showing the configuration as composed of two surfaces, a black square with a hole cut (checkerboard illustrates empty regions) on a white background. (b) An adaptation of (a), in which the black square is replaced with a black circular ring. (c) The black circular ring in (b), included within a Venn diagram along with a shaded circle. (d) A Venn diagram with the same shading as (c), but placed on a dark background, such that the regions that were shaded now has properties consistent with appearing as a hole (i.e., color similarity between interior and exterior of the contour).

same color (white), the white circular region tends to appear as a hole inside of a black surrounding square, revealing the white background below (see Fig. 3a, bottom). This percept occurs despite the fact that classic figure-ground cues (e.g., surrounded-ness, small region, convexity) suggest the white circle should be perceived as a figure on top of a solid black square (Rubin, 1915/1958; Kanizsa & Gerbino, 1976).

From this perspective, if the black region in Fig. 3a is reduced to just a circular ring as in Fig. 3b, the white inner region can be perceived as a hole through the ring, such that the white region belongs to the background. This ring in Fig. 3b corresponds to one of the circles that makes up a Venn primary diagram. Fig. 3c includes this circular ring within a Venn diagram, with parts of the diagram shaded gray. Once parts of the diagram become shaded, they no longer appear hole-like and instead appear more opaque. Yet, if that same diagram were placed on a dark background that matched the color of the shaded regions (Fig. 3d), the shaded regions would group with the background. Now, the shaded regions would appear hole-like, and the white region would appear more opaque. Thus, which regions in a Venn diagram may appear as holes should depend on configural relations in the image.

We propose that observers will infer that the regions appearing as holes (the emptiness in a surface) map to nonexistence (the emptiness of a class) in Venn diagrams. We call this the *hole hypothesis*. It follows that observers might also infer that the other, filled-in regions signify that everything (within the universe of discourse) belongs to the corresponding classes.[4] The hole hypothesis stems from the opaque-is-more bias previously observed in colormaps (Schloss et al., 2019). If greater opacity maps to "more," then a complete lack of opacity (i.e., transparency, or an apparent hole[5]) should map to non-existence. Thus, observers may ascribe meaning to the empty regions of Venn diagrams, originally intended not to encode meaning at all (Peirce, 1933; Shin, 1994; Venn, 1881).

Fig. 2 illustrates the contrast between the inferred mappings implied by the hole hypothesis and the conventional encoding established by Venn. Several examples of Venn diagrams are

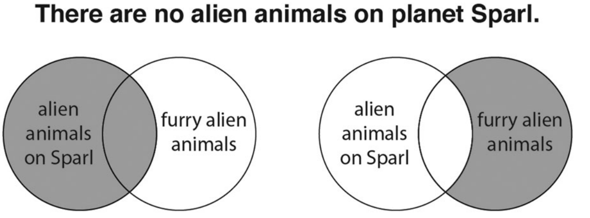

Fig 4. Example trial. If participants inferred that the dark regions mapped to non-existence, as in the conventional Venn system, they would choose the left diagram for the statement, “There are no alien animals on planet Sparl” and the right diagram for the alternate statement, “All furry alien animals are on planet Sparl.” If they inferred that the light regions mapped to non-existence, they would make the opposite choices.

given along with two possible English translations. In the middle column are the corresponding sentences if the diagrams were constructed such that shading means non-existence, as Venn intended. On the far right are the corresponding sentences if the empty, white regions signify non-existence as suggested by the hole hypothesis, given the white background. If we find evidence for the hole hypothesis, that would mean that inferred mappings for Venn diagrams depend on configural properties of the diagram. That is, the logical content that observers extract from a diagram would depend on how regions of the diagram interact with the background to form a holistic display.

1.3. Present study

In this study, we developed a new paradigm to assess inferred mappings for Venn diagrams. Participants were presented with a given statement, paired with two Venn diagrams (Fig. 4). Their task was to indicate which diagram best matched the statement. We constructed the diagram pairs such that participant responses revealed the nature of their inferred mappings. The two diagrams were inversions of each other—all regions that were light in one diagram were dark in the other diagram within the pair. For each given statement, participants would interpret one diagram as equivalent to the statement if they inferred that the darker regions mapped to non-existence and interpret the other diagram as equivalent to the statement if they inferred that lighter regions mapped to non-existence.

Consider the example in Fig. 4. Given the statement, “There are no alien animals on planet Sparl,” participants would choose the diagram on the left if they inferred that the darker regions map to non-existence, whereas they would choose the diagram on the right if they inferred that the lighter regions map to non-existence. Given an alternate statement, “All furry alien animals are on planet Sparl,” participants would choose the diagram on the right if they inferred the darker regions map to non-existence and the diagram on the left if they inferred that the lighter regions map to non-existence. By having participants choose diagrams for each statement, we determined the proportion of times participants inferred that the lighter or darker regions mapped to non-existence. These responses enabled us to assess the hole hypothesis. In this study, we did not directly assess perception of holes. We use the phrases “appearing as holes” and “apparent holes” in reference to regions that should be perceived as holes within a configuration, based on previous work on hole perception (Nelson & Palmer, 2001).

If the hole hypothesis is supported, that will mean Venn's (1881) suggestion that the most effective means to represent non-existence is "to just shade them out" is actually counterintuitive (at least if diagrams are presented on a white book page). Under such cases, shading out regions may be the *least effective* means to represent non-existence.

2. Experiment 1

Experiment 1 assessed whether people have systematic inferred mappings for Venn diagrams, and if so, whether those inferred mappings were modulated by the background lightness in a way that was consistent with the hole hypothesis. In Experiment 1A, we varied background lightness within-subjects. However, there was concern that demand characteristics may have led participants to respond in the same manner across different background conditions, obfuscating potential effects of the background that were predicted by the hole hypothesis. Thus, in Experiment 1B (and the remainder of experiments in this study) we varied background lightness between-subjects.

2.1. Methods

2.1.1. Participants

In Experiment 1A, there were 73 participants (*mean age* = 35.56, *SD* = 10.72; 48 males, 24 females, 1 did not disclose gender; gender was assessed using free response). In Experiment 1B, there were 145 participants (*mean age* = 37.62, *SD* = 12.39; 94 males, 45 females, 1 non-binary). Participants were sampled through Amazon's Mechanical Turk. All participants gave informed consent, and the UW-Madison Institutional Review Board approved the experimental protocol for this experiment and all subsequent experiments in this study.

2.1.2. Design and display

The display for each trial contained a statement at the top of the screen and two diagrams centered below the statement, presented side-by-side. The diagrams were 260 px $\times$ 157 px, which is equivalent to 6.88 cm $\times$ 4.15 cm on a 13.3-inch monitor at 2560 $\times$ 1600 resolution. In Experiment 1A, all participants saw 36 conditions: 3 pairs of diagrams $\times$ 2 statements per pair $\times$ 2 background colors $\times$ 3 domains. In Experiment 1B, participants only saw one background color (random assignment, light background: n = 73, dark background: n = 72). Thus, there were 18 trials (3 pairs of diagrams $\times$ 2 statements per pair $\times$ 3 domains). Otherwise, Experiments 1A and 1B were the same.

Fig. 5 shows the three pairs of diagrams, referred to as Diagram Pair a, b, and c. Each pair contained two Venn diagrams that were inversions of each other. To represent this inversion, below each diagram there is notation detailing which of these regions is shaded (represented as 1) or unshaded (represented as 0). The diagram on the left has the left and center regions shaded [1 1 0], and the diagram on the right has the inverse [0 0 1]. We always utilized Venn

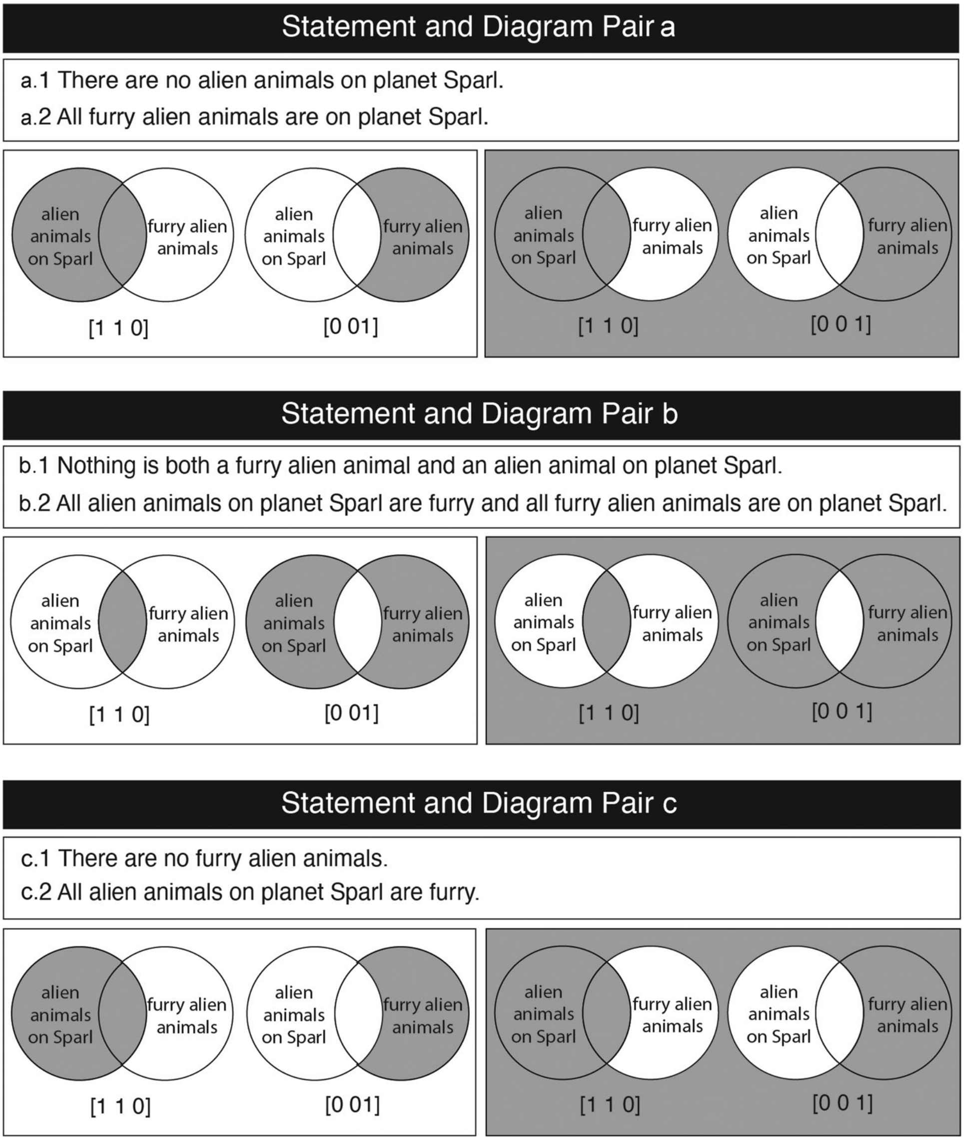

Fig 5. Three types of statement pairs tested in this experiment (a, b, and c), and corresponding diagram pairs below. All participants received Statement Pairs a–c matched with Diagram Pairs a–c, respectively. The diagram was shown on a light background in the “light” condition and on a dark background in the “dark” condition. Background lightness varied within-subject in Experiment 1A and between-subject in Experiment 1B and the remaining experiments. Numbers in brackets in this figure (1 = gray, 0 = white) are included to illustrate that the diagrams within each pair were inversions of each other. These numbers were not part of the experimental stimuli (see Fig. 4 for an example trial).

diagrams that had some combination of light/dark shading, as evidenced by the combination of zeroes and ones. Diagrams with no shading [0 0 0], and diagrams that were completely shaded [1 1 1], were excluded—a diagram with no shading is the primary diagram, so we excluded it and its inverse. It should be noted that we represented the Venn diagram as having three separate, meaningful regions. It is possible that participants may instead perceive the diagrams as simply containing two overlapping circles. We did not investigate this possibility here and designed the study according to the Venn encoding system, which treats each of the three regions separately.

For each diagram pair, we specified a statement pair. Within each statement pair, one contained "all" phrasing and one contained "no"/"nothing" phrasing. In Fig. 5, if participants inferred that the dark (i.e., shaded) regions mapped to non-existence, they would always choose the left diagram within each pair for Statement 1 and the right diagram for Statement 2. Although there were several ways to word each of the statements, we chose formulations that met the following criteria: relatively colloquial (e.g., "There are no" instead of "There does not exist"), non-redundant (e.g., "All furry alien animals are on planet Sparl" rather than "All furry alien animals are alien animals on planet Sparl") and decomposed (e.g.,"All A are B and all B are A" rather than "All and only A are B").

We also did not test statements that would require assigning logical significance to the color of the background. For example, to express not just that "All furry alien animals are on planet Sparl" but that "Everything is on planet Sparl" (or "Nothing is not on planet Sparl") one might use the background to encode the universe of discourse and then employ a visual feature such as shading to mark the rest of the background as "empty" (Shin, 1994). Evaluating certain disjunctions ("Either there are no alien animals on planet Sparl or all furry alien animals are on planet Sparl") might also require comparing different subdiagrams with potentially different backgrounds (Shin, 1994). We only investigated how participants interpreted the relationships between regions enclosed by connected circles.

We applied the experimental design shown in Fig. 5 to three domains within the fictitious alien planet Sparl: (1) alien animals, with the property of "furry" (as shown in Fig. 5), (2) alien houses, with the property "pointy", and (3) alien robots, with the property "grumpy." The three different domains served as replications. Trial order was randomized, and which diagram was on the left/right within each pair was also randomized for each participant. The Venn diagram images can be found on our OSF page (https://osf.io/awhf3/), and the background color was set within Qualtrics.

2.1.3. Procedure

Participants were asked to "imagine a universe with different alien planets, each of which could have the following things: alien robots, alien animals, alien houses. Each of these things could have different properties." They were then told, "during this study, you will be presented with 36 trials. Each trial will have a statement about one particular planet, called Sparl. Below the statement, there will be two diagrams. Your task is to indicate which diagram best matches the statement. Press next when you are ready to begin." During the experiment, participants saw each diagram and statement pair, one at a time in random order. To respond, they selected the radio button below the left or right diagram.

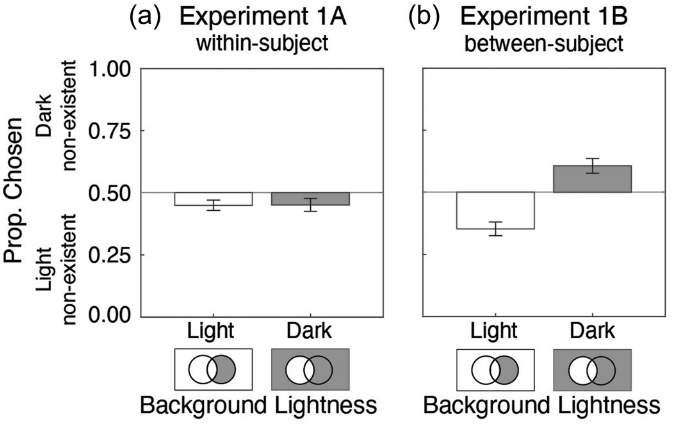

Fig 6. Results from Experiment 1, when background lightness varied (a) within-subject or (b) between-subject. The data show the mean proportion of responses consistent with inferring that the darker regions mapped to non-existence, plotted as a function of background lightness. Error bars represent standard errors of the means.

2.2. *Experiment 1A: Results and discussion*

Fig. 6a shows the mean proportion of times participants chose the diagram consistent with inferring that the darker regions mapped to non-existence, depending on background lightness in Experiment 1A. These data were obtained by calculating the proportion of responses out of the 18 trials for each participant (3 diagram pairs $\times$ 3 domains $\times$ 2 statements), and then averaging the proportions across participants. The raw data for this and all subsequent experiments can be found on our OSF page (https://osf.io/awhf3/).

The mean responses suggest a slight bias to infer that the lighter regions represent non-existence for both light and dark backgrounds. This observation was supported by a generalized mixed effects model (Bates et al., 2015; R version 1.3.1073, *lme4* 1.1-23, logistic regression, binomial family with the logit link function). The fixed effect was background lightness (coded as – .5 = dark background; .5 = light background), and the random effects were a by-subject random intercept, by-subject random slopes for background lightness, and a by-item random intercept. The intercept of the model represents the likelihood that responses were biased toward inferring that the dark regions mapped to non-existence across background conditions (i.e., Venn's original encoded mapping). The intercept was significant with a negative weight, suggesting that participants inferred that the light regions mapped to non-existence ($b = -0.31$, $\chi^2(1) = 6.76$, $p = .009$). There was no effect of background lightness ($b = -0.08$, $\chi^2(1) = 0.48$, $p = .48$).

The hole hypothesis suggests that participants would select the diagram consistent with the light regions signifying non-existence on a light background, and the dark regions signifying non-existence on a dark background. However, participants in this experiment reliably chose diagrams consistent with light regions signifying non-existence on both the light and dark backgrounds. This result did not support the hole hypothesis and is instead consistent with the dark-is-more bias (i.e., lighter regions mean less/non-existence). Responses are also consistent with the inference that filled-in regions (i.e., regions that do not match the background color) map to the concepts of "all" or "everything."

However, the lack of background effect may have been due to demand characteristics in this task. Participants may have adopted a strategy to be consistent across trials of the same diagram type, avoiding variation depending on the background color. Thus, their inferred mapping might have put larger weight on the dark-is-more bias, which is not background dependent. This concern was less relevant for previous work that showed a robust effect of background for colormaps, because the measure in that study was implicit (response time for accurate responses; Schloss et al., 2019), and implicit measures are less likely to be sensitive to demand characteristics than explicit measures like that used in the present study. To address this issue, we modified our experiment design in Experiment 1B to vary background lightness between-subjects, which enabled a purer test of background effects.

2.3. Experiment 1B: Results and discussion

Experiment 1B was identical to Experiment 1A, except we varied background lightness between-subjects rather than within-subjects. Fig. 6b shows the mean proportion of times participants chose the diagram that was consistent with inferring that the darker regions mapped to non-existence. Responses are separated by background lightness. We analyzed the data in the same manner as Experiment 1A except that background was a between-subject fixed effect and was not included in the by-subject random effects.

Unlike Experiment 1A, the intercept was not significant (suggesting no overall bias to infer that light was non-existent, $b = -0.12$, $\chi^2(1) = 0.93$, $p = .33$). Also, unlike Experiment 1A, there was an effect of background lightness, in which participants were more likely to interpret light as non-existent on light backgrounds than on dark backgrounds ($b = -1.47$, $\chi^2(1) = 28.18$, $p < .001$). Comparisons against chance for each background indicated that participants who saw the light background were more likely to respond as though light regions signified non-existence ($b = -0.85$, $\chi^2(1) = 23.54$, $p < .001$) and those who saw the dark background were more likely to respond as though dark regions signified non-existence ($b = 0.62$, χ^2 $(1) = 10.50$, $p = .001$). These results are consistent with the hole hypothesis; participants inferred that the regions whose perceptual properties were consistent with appearing as a hole signified that the corresponding class was empty.

Why did Experiment 1A show a dark-is-more bias and no evidence for the hole hypothesis, whereas Experiment 1B showed evidence for the hole hypothesis but not a dark-is-more bias? One possibility is that both factors are relevant to inferred mappings for Venn diagrams. In Experiment 1A, participants may have sought to be internally consistent for the same Venn diagrams seen on different backgrounds, so the non-background-dependent dark-is-more bias prevailed. In Experiment 1B, because the background varied between-subjects, participants did not need to consider internal consistency, and as such there was opportunity for effects of apparent holes to manifest. Within this account, the effect of apparent holes was stronger than the dark-is-more bias, so they dominated over the dark-is-more bias when they conflicted on the dark background. This is consistent with previous work on colormaps that suggested the opaque-is-more bias can override the dark-is-more bias when they conflict

(Schloss et al., 2019). However, open questions remain concerning what conditions determine the relative strength of these different biases, and why they differ in strength in the first place.

3. Experiment 2: Lightness-contrast

Experiment 1B suggested that inferred mappings for Venn diagrams are influenced by background lightness in a manner that is consistent with the hole hypothesis (i.e., light regions on light backgrounds signify non-existence and dark regions on dark backgrounds signify non-existence). However, an alternative account is that the background effects were driven by lightness contrast rather than percepts of holes. That is, it is possible that participants inferred that the lighter regions on light backgrounds signify non-existence and dark regions on dark backgrounds signify non-existence not because these regions appeared as holes, but rather because they contrasted less with the background.

In Experiment 2, we tested this alternative account by manipulating lightness contrast independent of whether conditions supported the percept of a hole. Based on a similar manipulation for colormaps (Schloss et al., 2019), we predicted that the background lightness would only influence inferred mappings for Venn diagrams when there was perceptual evidence for holes. In the absence of perceptual evidence for holes, inferred mappings should be dominated by the dark-is-more bias, such that participants choose diagrams that are consistent with lighter regions mapping to non-existence.

3.1. Methods

3.1.1. Participants

There were 294 participants (*mean age* = 35.55, *SD* = 11.16; 191 males, 99 females, one non-binary, three did not disclose), who were sampled through Amazon's Mechanical Turk. All gave informed consent.

3.1.2. Design, display, and procedure

The design, displays, and procedure were similar to Experiment 1B except we modified the colors of the Venn diagrams and the backgrounds. As in Experiment 1B, all participants completed 18 trials with the following within-subject factors: 3 pairs of diagrams × 2 statements per pair × 3 domains. We tested eight groups of participants with the following between-subject factors: 2 background lightness (light, dark) × 2 Venn diagram chromaticities (achromatic, chromatic) × 2 diagram/background chromaticity relations (match/mismatch).

As shown in Fig. 7, there were two chromaticity conditions for Venn diagrams, "achromatic" and "chromatic." In the achromatic condition, the light regions were light gray (CIE LCh = [85, 0, 0]) and the dark regions were darker gray (CIE LCh = [55, 0, 0]). In the chromatic condition, the light regions were peach with the same lightness as the light gray (CIE LCh = [85, 25, 50]), and the dark regions were teal with the same lightness as the dark gray (CIE LCh = [55, 25, 220]). We converted the coordinates from CIE LCh to CIELAB using standard equations (Wyszecki & Stiles, 1982), and converted from CIELAB to RGB using

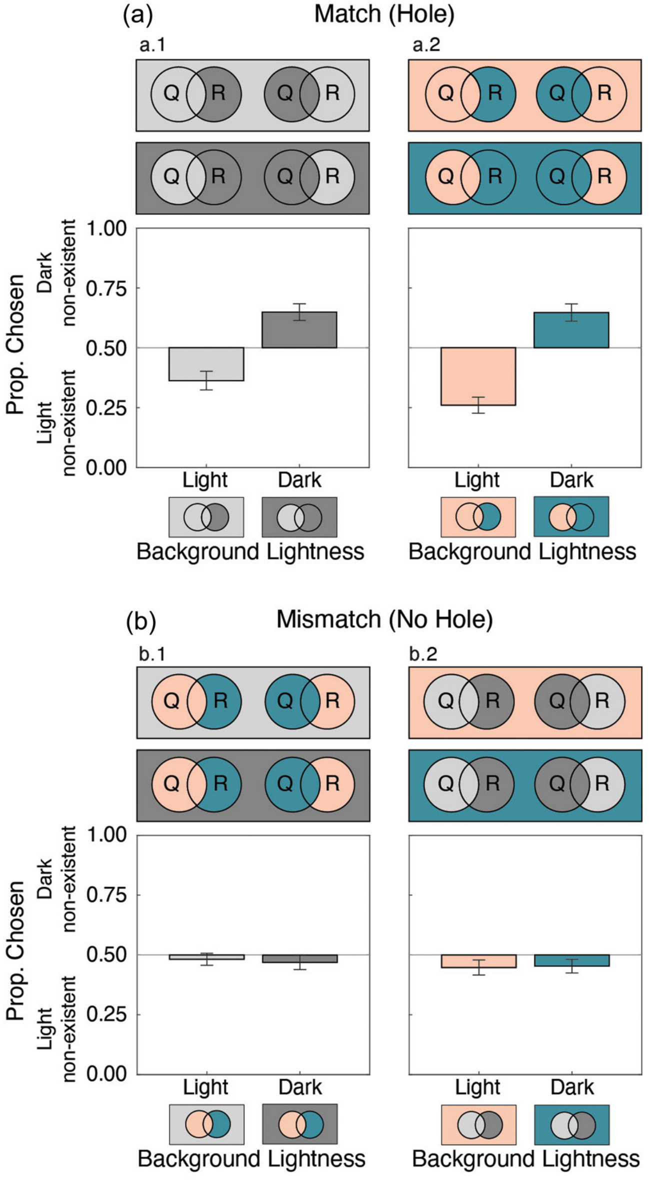

Fig 7. Experimental stimuli and results (a.1, a.2, b.1, b.2) from Experiment 2: (a) when the diagram and background match (hole), and (b) when the diagram and background mismatch (no hole). The results show the proportion of times participants chose the diagram consistent with inferring that the darker regions mapped to non-existence, depending on whether the background was light or dark (*x*-axis). Data are plotted separately for the diagram/background match conditions (a.1: achromatic; a.2: chromatic) and mismatch conditions (b.1: chromatic diagram/achromatic background; b.2: achromatic diagram/chromatic background). Error bars represent standard errors of the means

MATLAB's lab2rgb function, which makes standard assumptions about the monitor gamut and white point.

Color selection was done such that: (1) lightness (L*) was the same among light colors (light gray and peach) and among dark colors (dark gray and teal), (2) the chromatic colors differed in hue, (3) chroma (C*) was the same for the chromatic colors, and (4) participants with common color deficiencies could still perceive hue differences (checked using the proof colors for protanopia and deuteranopia in Adobe Illustrator). The achromatic condition was similar to Experiment 1 in that all the colors were achromatic, but here we used light gray instead of white. We made this change so we could hold lightness constant while varying chromaticity (achromatic vs. chromatic)—it is not possible to produce chromatic stimuli with the same lightness as white (where white is defined as the lightest color in CIELAB space). Further, by modifying the achromatic diagrams we were able to test both a near-direct and conceptual replication of Experiment 1.

Both diagram chromaticity conditions (achromatic or chromatic) appeared on each of two background chromaticity conditions (achromatic or chromatic). When the diagram and background chromaticities matched (achromatic diagram on achromatic background, or chromatic diagram on chromatic background), the configurations were consistent with perceptual evidence for a hole. When the diagram and background chromaticities were mismatched, the configurations were inconsistent with perceptual evidence for a hole.

3.2. *Results and discussion*

Recall that if the background effect depends on the percept of a hole and not just lightness contrast, then background lightness should modulate inferred mappings in the match conditions but not in the mismatch conditions. However, if the background depends on lightness contrast and does not require apparent holes, the background lightness should modulate inferred mappings for both the match and mismatch conditions.

Fig. 7 shows the mean proportion of times participants chose the diagram consistent with inferring that the darker regions mapped to non-existence depending on diagram/background match, background lightness, and diagram chromaticity.

To analyze the data, we constructed a generalized linear mixed effects model (logistic regression, binomial family with the logit link function). The fixed effects were diagram/background match (coded: -.5 = mismatch; .5 = match), background lightness (coded: -.5 = dark background; .5 = light background), and diagram chromaticity (coded: -.5 = achromatic; .5 = chromatic), and the random effects were a by-subject random intercept, a by-item random intercept, and a by-item random slope for diagram/background match, background lightness, and diagram chromaticity. Model results are presented in Table 1.

The intercept was significant, indicating that across all conditions, participants tended to choose the diagram consistent with light signifying non-existent. Background lightness was also significant overall, but the background interacted with the diagram/background match. Thus, we conducted a similar model but separated the data by diagram/background match vs. mismatch condition. Model results for match and mismatch conditions are presented in Table 2.

Table 1
Results from the full model in Experiment 2

Fixed Effect	b	SE	χ^2	p
Intercept	−0.15	0.06	6.65	.009**
Diagram/Bg match	0.04	0.12	0.12	.73
Bg lightness	−0.87	0.15	33.10	<.001***
Diagram chrom	−0.13	0.12	1.05	.30
Diagram/Bg match * Bg lightness	−1.75	0.28	38.13	<.001***
Diagram/Bg match * Diagram chrom	−0.46	0.24	3.66	.05
Diagram/Bg lightness * Diagram chrom	−0.23	0.24	0.89	.34
Diagram/Bg match * Bg lightness * Diagram chrom	−0.68	0.50	1.86	.17

Significance *$p < .05$, **$p < .01$, ***$p< .001$

Table 2
Results from the two models separated by diagram/background match and diagram/background mismatch in Experiment 2

	Fixed Effect	b	SE	χ^2	p
Experiment 2: Diagram/Bg match	Intercept	-0.14	0.11	1.84	.17
	Bg lightness	-1.87	0.28	44.46	<.001***
	Diagram chrom	-0.39	0.23	2.96	.08
	Bg lightness * Diagram chrom	-0.65	0.44	2.11	.15
Experiment 2: Diagram/Bg mismatch	Intercept	-0.16	0.06	6.78	.009**
	Bg lightness	0.01	0.13	0.008	.93
	Diagram chromaticity	0.10	0.13	0.68	.41
	Bg lightness * Diagram chrom	0.09	0.26	0.13	.72

Significance: *$p < .05$, **$p < .01$, ***$p < .001$

As seen in Fig. 7a.1 and 7a.2 and Table 2, the background had a significant effect in the match condition, with no effect of the intercept, and no interaction with chromaticity. This means that when Venn diagrams support the percept of a hole, participants were more likely to interpret light as signifying non-existence on light backgrounds than on dark backgrounds. Tests for each of the two background conditions against chance showed that for light backgrounds, participants were significantly more likely to choose the diagram consistent with light signifying non-existence ($b = -1.08$, $\chi^2(1) = 36.47$, $p < .001$), and that for dark backgrounds they were significantly more likely to choose the diagram consistent with dark signifying non-existence ($b = 0.79$, $\chi^2(1) = 20.22$, $p < .001$).

As seen in Fig. 7b.1 and 7b.2 and Table 2, background had no significant effect in the mismatch condition, nor was there a significant interaction with diagram chromaticity. However, there was a significant effect of the intercept. Taken together, these results indicate that participants chose the diagram consistent with light signifying non-existence in the mismatch conditions, with no effect of the background. This pattern reveals an overall dark-is-more bias for cases in which Venn diagrams do not have apparent holes.

In sum, the results of Experiment 2 rule out the account that the background effects were driven by lightness contrast rather than apparent holes. We found that background lightness only influenced inferred mappings for Venn diagrams when there was perceptual evidence for holes. In the absence of perceptual evidence for holes, participants inferred lighter regions map to non-existence (dark-is-more bias), similar to results for colormaps in the absence of apparent opacity variation (Schloss et al., 2019).

4. Experiment 3: Opacity versus hole

Thus far we have established that the background modulates inferred mappings for Venn diagrams in a manner that is consistent with the hole hypothesis. Recall that the hole hypothesis extends from the opaque-is-more bias previously observed in colormaps (Schloss et al., 2019). The logic was that if greater opacity maps to "more" and less opacity maps to "less," then a complete lack of opacity (i.e., transparency, or an apparent hole) should map to non-existence. The hole hypothesis goes beyond the opaque-is-more bias in assigning a privileged role to fully transparent regions (apparent holes) in representing non-existence. It is not merely that observers will infer that the less opaque regions in a diagram (regions which may still be somewhat opaque) map to non-existence; observers should be especially likely to infer that the regions map to non-existence if it lacks opacity altogether.

In Experiment 3, we investigated whether the presence of an apparent hole had an effect beyond the opaque-is-more bias. We assessed whether background modulates inferred mappings for Venn diagrams in a manner that is consistent with the opaque-is-more bias, even in the absence of an apparent hole. To address this question, we used stimuli in which there was perceptual evidence for opacity variation,[6] but the least opaque regions appeared translucent rather than fully transparent (i.e., an apparent hole).

We used the same achromatic Venn diagrams from Experiment 2 but made the light background lighter (white) and the dark background darker (dark gray). Thus, we could directly compare the results from data collected in this experiment with the achromatic match condition in Experiment 2, as the only difference was the colors of the backgrounds. If we find an effect of the background in the absence of perceptual evidence of a hole, that will suggest the opaque-is-more bias operates independently of an apparent hole. But, if the background effect is weaker when there is no perceptual evidence for a hole, that would suggest there is something special about empty regions representing non-existence, distinct from merely the least opaque regions representing non-existence.

4.1. Methods

4.1.1. Participants

There were 146 participants (*mean age* = 37.11 years, *SD* = 11.65 years; 90 males, 56 females), who were sampled through Amazon's Mechanical Turk. All gave informed consent.

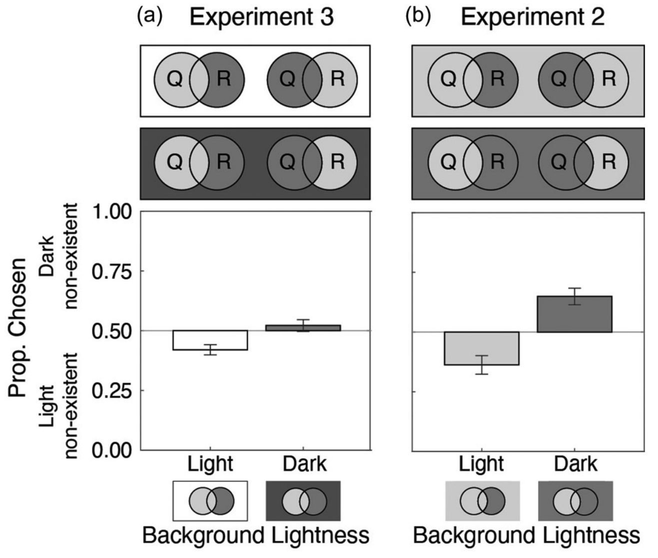

Fig 8. Experimental stimuli and results of Experiment 3 (a), and corresponding stimuli and results from Experiment 2 (b; previously shown in Fig. 7a.1). The results show the mean proportion of times participants chose the diagram consistent with inferring that the darker regions mapped to non-existence as a function of light/dark background. Error bars represent standard errors of the means.

4.1.2. Design, displays, and procedure

The design and procedure were identical to Experiment 1B, except we modified the colors of the Venn diagrams and background. The Venn diagrams were the same as the achromatic diagrams in Experiment 2. However, in this experiment the light background was white, and the dark background was extra dark gray, which created a translucent appearance as opposed to the percept of a hole (refer to Fig. 8a.1). Participants were randomly assigned to background group (light: $n = 74$, dark: $n = 72$).

4.2. Results and discussion

We tested the hole hypothesis by examining if background lightness had a larger effect when there was perceptual evidence for a hole (Experiment 2, Fig. 8b), compared with when there was apparent opacity variation but no hole (Experiment 3, Fig. 8a). We used a generalized linear mixed effects model with fixed effects including opacity (coded: $-.5$ = translucent [Experiment 3]; $.5$ = hole [Experiment 2]) and background lightness (coded: $-.5$ = dark background; $.5$ = light background). The random effects were a by-subject random intercept, a by-item random intercept, and a by-item random slope for diagram/background match and background lightness.

Fig. 8 shows the mean proportion of times participants chose diagrams consistent with inferring that the darker regions mapped to non-existence, separated for the light and dark background. There was an overall effect of background ($b = -0.98$, $\chi^2(1) = 24.56$, $p < .001$), but critically, background interacted with opacity ($b = -0.96$, $\chi^2(1) = 9.81$, $p = .001$).

The effect of background was larger when the less opaque regions were fully transparent (i.e., supported the percept of a hole) (Fig. 8b) than when it appeared translucent (Fig. 8a). This result supports the hole hypothesis: Participants are especially likely to infer that less opaque regions map to non-existence when those regions appeared as holes. Additionally, the intercept was not significant, suggesting no overall dark-is-more bias ($b = -0.05$, $\chi^2(1) = 0.42$, $p = .51$) and the main effect of opacity was not significant ($b = 0.20$, $\chi^2(1) = 1.52$, $p = .22$).

Next, we tested for evidence of the opaque-is-more bias in isolation by testing if background lightness had an effect when there was apparent opacity variation and no apparent hole (Experiment 3, Fig. 8a). We analyzed the data using the same mixed-effect regression as in Experiment 1B. Overall, the intercept was not significant ($b = -0.14$, $\chi^2(1) = 3.26$, $p = .07$), suggesting no overall dark-is-more bias, but there was an effect of background lightness ($b = -.48$, $\chi^2(1) = 7.66$, $p = .005$). Participants in the light background condition were significantly more likely to interpret light as non-existence than those in the dark background condition. This result is consistent with the opaque-is-more bias (i.e., less opaque signifies non-existence). Comparisons against chance indicated that participants in the light background condition were significantly more likely than chance to infer light was non-existent ($b = -0.38$, $\chi^2(1) = 9.66$, $p = .002$), but those in the dark background condition were no different from chance ($b = 0.09$, $\chi^2(1) = 0.80$, $p = .37$). This pattern is consistent with observers having a dark-is-more bias and opaque-is-more bias, which work together on the light background and cancel out on the dark background.

In summary, this experiment suggests that the percept of a hole plays an important role in inferred mappings for Venn diagrams, beyond that which can be explained by opacity variation alone. Directly comparing the results from Experiment 3 with the achromatic diagram/background match condition from Experiment 2, we found that background lightness had a larger effect when there was perceptual evidence for a hole compared to when there was merely perceptual evidence for opacity variation. Still, the results of Experiment 3 revealed an effect of background lightness, even without the percept of a hole. This provides evidence for the opaque-is-more bias, even in the absence of conditions that support the percept of a transparent hole.

5. General discussion

In this study, we examined whether inferred mappings previously observed for colormaps extend to Venn diagrams. We tested a new hypothesis, the *hole hypothesis*, extending from the opaque-is-more bias. The hole hypothesis specifies that people infer that the regions appearing as holes in logical diagrams represent "non-existence" (i.e., that *nothing* belongs to the corresponding class). This hypothesis suggests that established conventions for Venn diagrams do not align with inferred mappings of observers. According to that established convention, darker regions in Venn diagrams encode the emptiness of the corresponding classes, whereas unfilled regions that appear as holes do not encode any meaning about whether the corresponding class is empty or not. Results across Experiments 1–3 supported the hole hypothesis and challenge established conventions. Participants chose diagrams to match logical propositions in a manner that was consistent with inferring that the unfilled regions appearing as holes mapped to non-existence. Responses were also consistent with the inference that filled-in regions (i.e., regions that do not match the background color) map to concepts of "all" or "everything."

In the absence of apparent holes in Experiment 2 mismatch condition, participants inferred that the lighter regions mapped to non-existence regardless of the background lightness, which is consistent with the dark-is-more bias. This finding rules out the interpretation that inferred mappings are merely based on local lightness contrast across edges because lightness contrast with the background only had an effect in the match condition when there was perceptual evidence for holes. This pattern of results suggests that configural processing that organizes the input surfaces at distinct depth planes (i.e., regions with a hole on top of a background) is responsible for the effects of the background color on inferred mappings. These results mirror previous reports that the background only has an effect when colors in colormaps appear to vary in opacity and that in the absence of opacity variation the dark-is-more bias prevails on light and dark backgrounds (Schloss et al., 2019).

In Experiment 3, in the absence of apparent holes but the presence of perceptual evidence for opacity variation, we found that background lightness had an effect consistent with the opaque-is-more bias. That is, participants were more likely to choose diagrams consistent with lighter regions mapping to non-existence when the regions appeared less opaque. However, this background effect was weaker for these diagrams compared with diagrams in Experiment 2, which had perceptual evidence for holes. This interaction suggests that the perceptual emptiness of regions has a privileged role in signifying the emptiness of the corresponding class (i.e., non-existence).

The one exception, in which there were apparent holes but no effect of the background, was in Experiment 1A. Background varied within-subjects which raised a concern about demand characteristics influencing participants to be internally consistent (see Experiment 1A for a discussion of this issue). In this case, participants inferred that light mapped to non-existence on light and dark backgrounds, contrary to Venn's assertion that the most effective means to represent non-existence in regions of his diagrams are "just to shade them out."

In this study, we aimed to understand the nature of people's inferred mappings for Venn diagrams, but we did not set out to redesign the Venn system. Creating an intuitive, comprehensive encoding system for logical statements is riddled with complexities that are far beyond the scope of the present work. One issue is that the Venn system is limited in its expressive power, and more complex systems are needed to encode certain logical contents (Peirce, 1933; Shin, 1994). Venn's original system cannot express all possible disjunctions (e.g., "Either all alien animals are on planet Sparl or all alien animals are furry") or existential propositions (e.g., "Some alien animals are on planet Sparl"; "There exists something that is neither an alien animal on planet Sparl nor a furry alien animal"). Venn's system can be modified to address these limitations by introducing additional visual features to indicate *existence* and to indicate *disjunctive information* (Peirce, 1933; Shin, 1994).

These modifications add visual and semantic dimensions to the diagrams that can affect an observer's inferred mappings and complicate the "naturalness" with which the diagrams can be used for logical inference. For example, systems tend to use an "x" to indicate the existence in regions of the diagram (Peirce, 1933; Shin, 1994), which may be intuitive (e.g., " 'x' marks the spot") or counterintuitive (e.g., "x" means crossed out, or absent). It has been claimed that there is a "trade-off" between the expressiveness of a diagram and its naturalness or tractability for visual reasoning (Stenning & Oberlander, 1995). Understanding this trade-off and how to maximize naturalness or interpretability, is a ripe area for future research.

A second issue is that even within the context of the original Venn system, we have set aside the logical content that can be encoded in the background. In the original Venn system, shading out the background expresses that nothing exists outside the classes signified by the circles in the diagram. Shading out the background allows one to express, for example, "Everything is an animal on planet Sparl." In the present study, we simplified the encoding system by assuming that the background does not encode meaning. However, special difficulties arise when we consider the interpretation of shaded regions in relation to the interpretation of a shaded background.

For example, consider a Venn diagram on a light background (Fig. 3c). Our results are consistent with the conclusion that people will infer that the non-shaded regions (i.e., apparent holes) map to non-existence and that shaded regions do not map to non-existence and perhaps signify the classes containing everything in the universe of discourse. But, consider holding the shading properties within the circles constant but making the background dark (Fig. 3d). This reverses which regions appear filled and which regions appear empty within the diagram: shaded regions now provide conditions consistent with the percept of a hole. Consequently, our results suggest people will now infer that the shaded regions within the circles of the diagram map to non-existence. Thus, changing the information encoded in the background would have collateral effects on inferred mappings within the circular regions. In general, our results demonstrate that shading in regions is not necessarily an isolated intervention on a diagram. In changing the relationships between the colors of different regions of a diagram, shading can introduce configural effects that might influence an observer's interpretation of the diagram.

The fact that shading in regions can produce configural relationships that affect the interpretation of a diagram should be taken into account in future studies of the interpretation of diagrams in the context of inference- or proof-like procedures for manipulating and updating those diagrams (Shin, 1994). Future work might investigate how observers' interpretations of individual diagrams, as studied here, influence their evaluation of the logical validity of sequences of diagrams (e.g., a sequence that expresses a syllogistic inference).

In the present study, we focused on interpreting existing diagrams, but it may be that the act of producing and manipulating diagrams itself influences their interpretation. In creating and updating diagrams, one is engaged in both "drawing" and "reading." Venn constructed his diagrams via drawing, which is likely why he crossed out regions (i.e., dark shading) in the Venn diagrams to represent non-existence. There could be notable differences in the use and interpretation of visual features depending on whether a person is actively constructing a diagram (as Venn did) or interpreting already constructed diagrams (as participants in our study did). Similar questions concern how observers interpret existing diagrams when they are engaged in actively manipulating those diagrams, by adding or removing visual features.

For example, imagine participants were presented with an unannotated and/or primary Venn diagram and were asked to place the phrases "alien animals on planet Sparl" and "furry alien animals" into regions of the Venn diagram given the sentence "There are no alien animals on planet Sparl." Based on the shading of the Venn diagram (or if they themselves are asked to shade the regions), it is possible that the physical act of shading and/or placing elements of the sentence into a Venn diagram could influence peoples' understanding of what logical proposition the diagram represents.

In conclusion, this study has shown that there are systematic constraints on how observers infer mappings between logical concepts and visual features in Venn diagrams. These constraints place limits on how natural it is for observers to recover the intended meanings of diagrams and in some cases lead to interpretations that conflict with the designer's intentions. The differences between the conventional design of Venn diagrams and observers' unguided interpretations can reveal the systematic strategies by which observers make sense of visual representations of information. The key finding here is that observers rely on the relationship between the color of a region and the color of the background when inferring the logical content of a diagram, with a notable tendency to infer that an apparent hole signifies that nothing exists in the corresponding class. As with other forms of visual representation such as colormaps, we have shown that observers do not assign concepts to visual features in isolation, but instead rely on the configural relationships that arise between visual features in the diagram.

Acknowledgments

The research reported here was supported by the Institute of Education Sciences, U.S. Department of Education, through Award #R305B150003 to the University of Wisconsin–Madison. This material is based upon work supported by the National Science Foundation under Grant No. BCS-1945303 to K.B.S. This work was also supported by the Vision: Science to Applications (VISTA) program, thanks in part to funding from the Canada First Research Excellence Fund. Additional support for this research was provided by the Office of the Vice Chancellor for Research and Graduate Education at the University of Wisconsin-Madison with funding from the Wisconsin Alumni Research Foundation. The opinions expressed are those of the authors and do not represent views of the U.S. Department of Education. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. We thank members of the Visual Reasoning Lab and the anonymous reviewers for their valuable feedback on this work.

Conflicts of interest

The authors have no conflicts to disclose.

Notes

1 The term "inferred" in "inferred mappings" indicates that these mappings are observers' best estimates of how visual features should map to concepts in the context of a particular encoding system, distinct from explicit legends or labels (Schloss et al., 2018). The term is agnostic to whether these inferences are conscious or unconscious and does not imply that these mappings depend exclusively on high-level reasoning beyond perceptual processing. Inferred mappings are only one factor that goes into the larger set of processes involved in interpreting diagrams, which in the case of Venn diagrams also involves logical inference.

2 Configural, or holistic properties are "emergent properties that cannot be predicted by considering only the individual component parts or their simple sum. Rather, they arise from the *interrelations* between the parts comprising strong configurations" (Wagemans et al., 2012, p. 8).

3 See Shin (1994) for a contemporary systematic treatment of the semantics of Venn diagrams.

4 It is possible that observers infer that the filled-in regions signify that the corresponding class is non-empty (i.e., there exist entities in that class), but the present study was not designed to test for that possibility.

5 In the physical world, a hole is distinct from a transparent surface because a hole arises from the absence of matter and a transparent surface arises from matter that is fully "see-through." However, from a perceptual perspective, a hole and a fully transparent surface should appear the same.

6 Classically, perceptual transparency is discussed in terms of a homogeneous surface that does not vary in opacity being placed on a heterogeneous surface that varies in lightness (Beck & Ivry, 1988; Metelli, 1974; Singh & Anderson, 2002). However, perceptual transparency can arise for a surface placed on a homogeneous background (Ekroll, Faul, & Niederée, 2004). When the opaque-is-more bias was introduced for colormaps, it was considered with respect to the latter (Schloss et al., 2019), where a heterogenous surface was placed on a homogeneous background. Here, we also focus on the latter, considering opacity variation with respect to three separate regions (Fig. 1) on a homogeneous background. The assumption is that the regions that contrast least with the background appears least opaque (i.e., the lightest regions on a light background, the darkest regions on a dark background). This assumption hinges on the premise that the colors within the configuration vary in a manner that approximates a linear interpolation between the highest contrast color and the background (Schloss et al., 2019). However, we acknowledge that additional complexities arise concerning apparent transparency in Venn diagrams when treated as overlapping circles. Addressing those complexities is beyond the scope of the present study.

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