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The "Crowd Size Illusion" and the Relativity of Number Perception

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Abstract

When we investigate busy visual scenes, how do we estimate the number of objects that we see? Most work on number perception answers this question by focusing on properties of the to-be-estimated set of objects—their number, their size, their relative position, and so on. Here, in contrast, we show that perceived number is influenced by extraneous visual information. In six experiments, participants were shown "crowds" of dots that filled "seats" in a visual grid, asking whether the perceived number is influenced not only by the number of *occupied* seats, but also the number of *unoccupied* seats. When only about 15%–30% of the "seats" were filled, people perceived *fewer* dots (compared to displays without any grid). We further demonstrated that this illusion depends on the proportion of occupied seats. When most "seats" were filled, the illusion reversed: People perceived the grid displays as having *more* dots. This effect is continuous, switching directions at around the 50% occupancy mark. Moreover, this "crowd size illusion" is phenomenologically robust: It is evident in simple visual displays, even when the observer is aware they are being tricked. We discuss these findings in light of the recent hypothesis that the number system represents number in a part–whole format.

Keywords: Number; Perception; Illusion

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1. Introduction

Imagine you are giving a presentation in a large auditorium. From the podium, you look out at what must be a few hundred seats. Many people showed up, but a large number of seats remain empty nonetheless. The room feels oddly vacant. Why? One possibility is that pessimism about the number of people in an audience reflects a bias in thinking: Perhaps we feel self-conscious and underestimate the number of attendees as a result. Another very different possibility is that these impressions reflect not a bias of our *thinking* but a constraint on our ability to visually judge the number of people in the audience in the first place. Here, we explore the latter possibility—that the ability to perceive numerical information is systematically constrained and distorted by irrelevant numerical information (in this case, empty "seats"). We examine a single case study of such distortions, which we call the *crowd size illusion*.

The ability to perceive number is thought to be a unique process, a consequence of the evolutionarily ancient "approximate number system," which governs both the perception and cognition of number (see Feigenson, Dehaene, & Spelke, 2004; Halberda, Mazzocco, & Feigenson, 2008). Particularly intriguing is the fact that numerical acuity, as measured by simple number discrimination tasks, is thought to be related to higher-order mathematical cognition: One's numerical "Weber fraction" is predictive of mathematical achievement on standardized tests, for instance (Halberda et al., 2008). In this way, the mechanisms underlying the perception of number are thought to be deeply related to mathematical cognition more broadly. Learning about one invariably informs the study of the other.

The "approximate number system" has been studied extensively (see Odic & Starr, 2018). While some debates about its nature remain (see Clarke & Beck, 2021; Leibovich, Katzin, Harel, & Henik, 2017), many features of the "approximate number system" are well-established. For example, the "approximate number system" is thought to be (a) prelinguistic (it develops independently from and is not dependent on, language), (b) imprecise (in contrast with a "small number" system; Feigenson et al., 2004; Margolis, 2020; see also Cheyette & Piantadosi, 2020), and (c) consistent with Weber's law (such that the system is sensitive to relative rather than absolute differences). Relatedly, there is consensus that the approximate number system is genuinely *perceptual* in nature, such that it should be studied in the same way as visual attributes like color, motion, and size (Burr & Ross, 2008; but see Yousif, Clarke, & Brannon, 2024, 2025).

Even so, the mechanisms underlying number approximation remain elusive—in part, perhaps, because number approximation is *illusive*. There is a wide variety of visual factors that influence number perception. For instance, number perception is (infamously) influenced by other spatial properties like density and area, to the extent that it has been questioned whether the perception of any visual quantities could ever be studied in isolation (see Aulet & Lourenco, 2021, 2023; Gebuis & Reynvoet, 2012a, 2012b; Hurewitz, Gelman, & Schnitzer, 2006; Leibovich et al., 2017; Yousif & Keil, 2020, 2021). Perceived number is also influenced by subtle visual features like the orientation of items in a display (DeWind, Bonner, & Brannon, 2020), their "contextual coherence" (Qu, Bonner, DeWind, & Brannon, 2024), visual connections between items (Franconeri, Bemis, & Alvarez, 2009; He, Zhang, Zhou, &

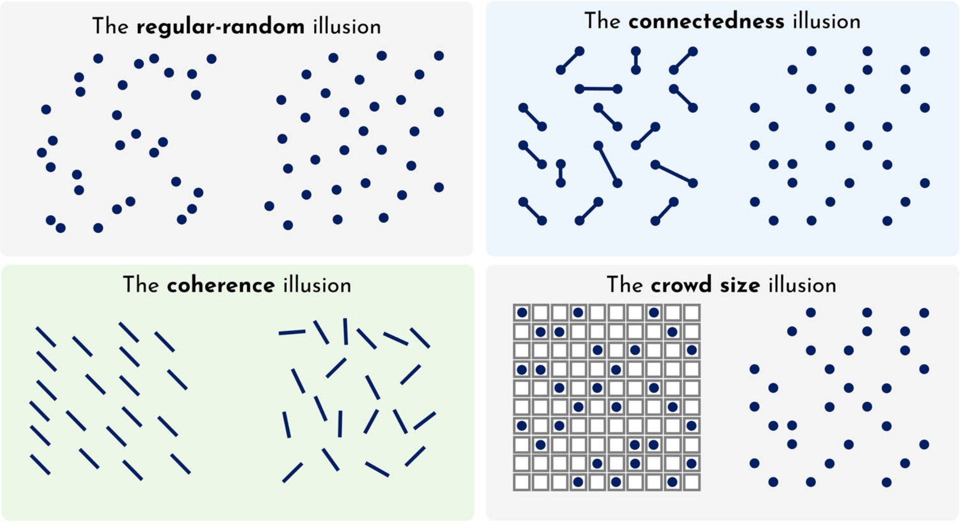

Fig. 1. Numerical illusions. The regular-random illusion describes the fact that more regular displays are perceived as more numerous than less regular displays (Ginsburg, 1976). The connectedness illusion describes the fact that connected sets of objects are perceived as less numerous than equivalent but unconnected sets of objects (Franconeri et al., 2009; He et al., 2009). The coherence illusion describes the fact that more coherent displays (e.g., wherein the objects are all of a similar orientation) are perceived as more numerous than less coherent displays (DeWind et al., 2020). The crowd size illusion describes the fact that, as is evident here, the presence of irrelevant numerical information (here in the form of an extraneous grid) influences perceived number.

Chen, 2009; Yousif, Clarke, & Brannon, 2025), the arrangement of the to-be-estimated items (Ginsburg, 1976; see also Yu, Xiao, Bemis, & Franconeri, 2019), their topological structure (Yousif & Brannon, 2025), or even the presence of other, non-numerical visual illusions (Picon, Dramkin, & Odic, 2019). A full account of visual number estimation would require a coherent theory that explains all varieties of numerical illusions at once—a feat that would seem to require a full account of visual perception.

The illusive nature of number perception reveals something critical about the "approximate number system": that it interacts in complex, sometimes striking, ways with other visual processes (see DeWind et al., 2020; Franconeri et al., 2009; Picon et al., 2019). One can easily appreciate the perceptual nature of these illusions for themselves: A display with 20 connected dots is perceived as *obviously* fewer in number than a display with 20 unconnected dots (see Fig. 1). This case is particularly striking not only because the illusion is resistant to anything you *think* or *know* about the display, but because it constitutes a case in which *adding* something to a display effectively *reduces* its perceived number. This contradiction points to a sophisticated mechanism of number approximation, which (a) does not depend solely on simple heuristics (i.e., more = more), and (b) engages perceptual mechanisms related to objects, both for visually describing the items to be enumerated (e.g., "object-based attention"; see Franconeri et al., 2009; Scholl, 2001; Yu et al., 2019) and for attending and remembering numerical information for sets of items (Halberda, Sires, & Feigenson, 2006).

Most models of number perception assume that the "approximate number system" roughly approximates whatever we expect it to approximate. In other words, models do not typically try to account for the influence of irrelevant visual features, despite the fact that we know of many numerical illusions that arise from the manipulation of seemingly irrelevant visual features (e.g., DeWind et al., 2020; Franconeri et al., 2009; Ginsburg, 1976; Picon et al., 2019). In the real world, of course, number estimation is messy: If we are looking out on a crowd in a park, we are tasked not only with estimating the number of people in that crowd but *ignoring* the number of legs, or leaves, or lampposts. (*How* the approximate number system knows what to estimate is a mystery for another day.) Indeed, the number of lampposts and leaves should not influence the estimate of the size of the crowd at all. Yet, in practice, we know that number estimation is influenced by all sorts of factors (see Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2011; DeWind et al., 2020; Gebuis & Reynvoet, 2012a, 2012b; Leibovich et al., 2017; Picon et al., 2019)—suggesting that this sometimes-simplified view of number perception fails to capture how number perception occurs in real scenes.

A potentially striking fact about the aforementioned *crowd size illusion*—if there is such an illusion—is that it reveals a case where the perception of one attribute (e.g., the number of people in a crowd) is heavily influenced by an unrelated feature (e.g., the number of seats those people may or may not occupy). In fact, it would reveal a case where *extra* information (i.e., objectively *increasing* the visual information in a scene) results in a *decrease* in perceived number—in much the same way that adding lines to connect dots results in a decrease in their perceived number (Franconeri et al., 2009). Such cases are revealing because they demonstrate perceptual mechanisms powerful enough to overcome a simple "more is more" bias. They demand, therefore, a more nuanced account of number perception.

1.1. Current study: The "crowd size illusion"

The goal of the current study is to ask, first and foremost, whether a "crowd size illusion" exists. To foreshadow, it does: Observers robustly perceive the numbers of dots in relatively "empty" crowds (as operationalized by empty boxes arranged in a grid) to be fewer in number than equivalent displays of only dots. This illusion is powerful enough that you can easily see it for yourself (see Fig. 1; Experiment 1).

Having established that some version of a "crowd size illusion" is genuine, we then demonstrate that it is sufficiently robust to manifest not only in a comparison task, but in an estimation task (in which participants estimate the number of items in individual displays with or without empty "seats"; Experiment 2). We further show that the crowd size illusion varies as a function of the proportion of occupied seats: While proportionally small crowds are robustly underestimated in size, the opposite is true of proportionally large crowds (i.e., ones that occupy a majority of possible "seats"; Experiments 3 and 4). Finally, we show that the "empty" seats are critical to the illusion, finding that removing them (while keeping the "full" seats) eliminates the illusion. All told, these results point to a robust, and potentially counterintuitive, illusion of number perception.

2. Experiment 1: Comparison task

First, we investigated whether the presence of "empty seats" in a crowd (operationalized by a grid of boxes) would cause a decrease in perceived number. We created stimuli composed of a varying number of blue dots, some of which contained a grid pattern of grey boxes. Participants were shown two stimuli, one with a grid and one without, for a brief interval and then asked to determine which had more dots (see Fig. 2a). We predicted that people would be more likely to indicate that the stimuli without the grid contained more dots.

2.1. Methods

For this experiment, and all subsequent experiments in this paper, the sample sizes, primary dependent variables, and key statistical tests were chosen in advance and were preregistered (see OSF: https://osf.io/vdsyw/).

Participants. Fifty participants were tested online via Prolific. The exclusion criteria were highly conservative, and thus no participants were excluded. This study was approved by the relevant Institutional Review Board.

Stimuli. All stimuli in this experiment were displays of blue (#257187) dots, ranging in number from 35 to 200. The positions of the dots were randomly assigned to "cells" in a 25 × 25 grid, without jitter. On each trial, participants saw two stimuli side-by-side, each 400 by 400px. One of the displays only contained blue dots; the other contained blue dots superimposed on a visible 25×25 grid, where each "cell" was marked by a light grey (#A8A8A8) box. The side containing the grid was counterbalanced. There were seven possible default number combinations (left stimulus, right stimulus): [70,100],[80,100],[90,100],[100,100],[100,90],[100,80],[100,70]. Additionally, each trial had a "multiplier" of either 0.5, 1, or 2 on these base values to increase variety in the displays. There were two distinct instances of combination of the above features, resulting in a total of 84 trials (7 default number combinations × 3 multipliers × 2 grid locations [grid on left, grid on right] × 2 unique instances).

Procedure. On each trial, the stimuli flashed on the screen for 1 s. Participants were asked to indicate which side had more blue dots by pressing "q" for "left" or "p" for "right." It was emphasized to participants that they must indicate which side contained more dots, irrespective of the presence of the grid boxes. After each response was recorded, there was a 750 ms inter-trial interval. Each participant completed 84 trials in a random order. Prior to beginning the task, they completed four representative practice trials, the data from which were not recorded.

2.2. Results and discussion

The results of Experiment 1 can be seen in Fig. 2b,c. We first checked that participants were appropriately sensitive to the true number of blue dots. Overall, participants selected the side with the greater number of blue dots 67% of the time, $t(49) = 15.64$, $p < .001$, $d = 2.21$. As is evident from the figures, participants tended to indicate that the side *without* the grid was more numerous ($M = 59.8\%$, $SD = 18.5\%$; $t(49) = 3.73$, $p < .001$, $d = 0.53$) across all

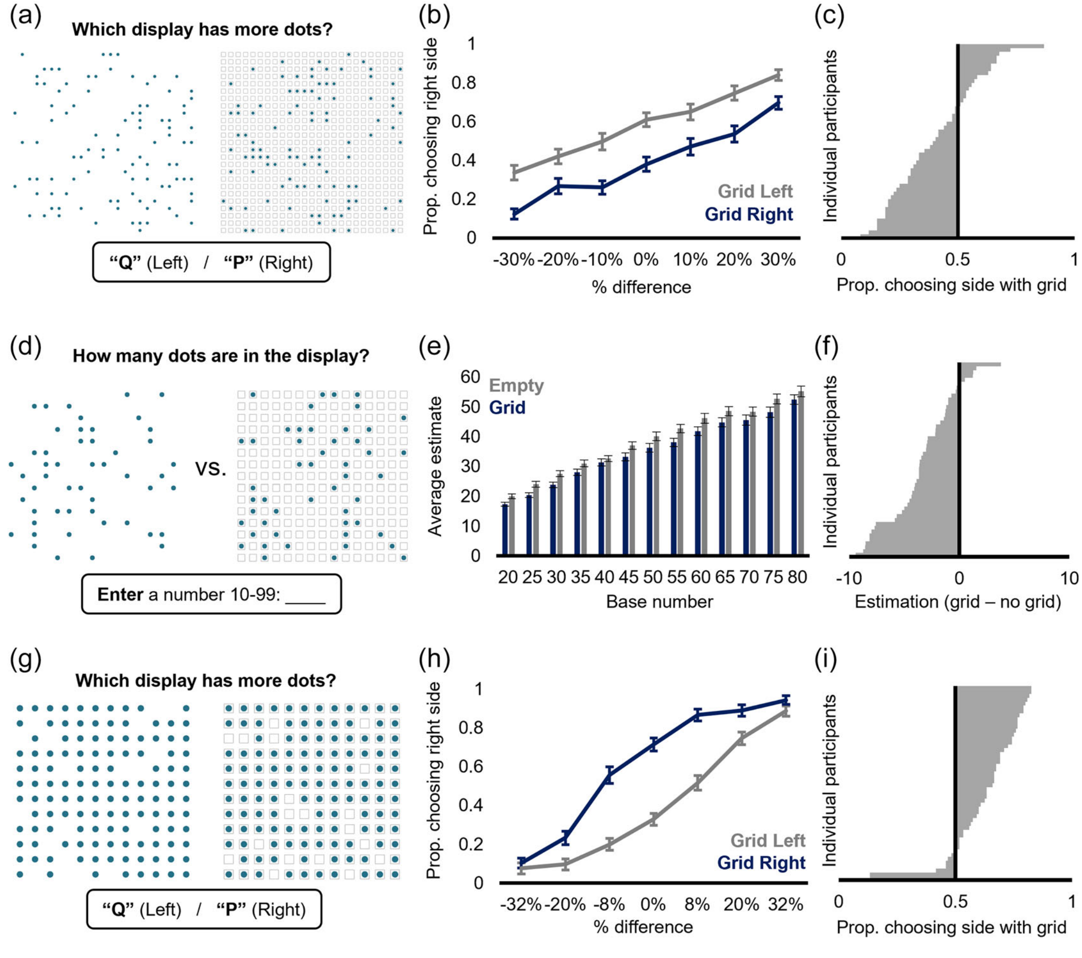

Fig. 2. Example stimuli and design of Experiments 1, 2, and 3. Example displays for each experiment are equal in number. Error bars represent ± 1 *SEM*. (a) In Experiment 1, participants compared sets of blue dots arranged in a 25 × 25 grid. On each trial, the grid was visible on only one side of the display. (b) Participants tended to choose the right side when the grid was on the left more than when the grid was on the right. (c) Participants tended to indicate that the side without the grid had more dots. (d) In Experiment 2, participants estimated the number of dots arranged in a 15 × 15 grid. The grid was visible in half the trials. (e) Participants estimated fewer dots in grid stimuli than non-grid stimuli. (f) Participants tended to estimate fewer dots in displays with the grid. (g) In Experiment 3, participants compared sets of blue dots arranged a 12 × 12 grid, in which most cells in the grid were occupied. On each trial, the grid was visible on only one side of the display. (h) Participants tended to choose the right side when the grid was on the right more than when the grid was on the left. (i) Participants tended to indicate that the side with the grid had more dots.

differences in number. Thirty-four out of the 50 participants chose the side without the grid more often than not (binomial test, $p = .008$). The effect was similar when accounting only for trials in which the displays were equal in number ($M = 61.5\%$, $SD = 21.7\%$; $t(49) = 3.74$, $p < .001$, d $= 0.53$).[1] Thus, these results indicate that the presence of empty cells in a grid robustly decreases perceived number.

3. Experiment 2: Estimation task

How powerful is the *crowd size illusion*? Is it robust enough that it will be evident in an estimation task (in which participants never directly compare displays with and without grids, thus eliminating possible task demands or response conflicts; see Picon et al., 2019)? In a second experiment, participants were shown one stimulus at a time and asked to estimate the number of blue dots in the display (see Fig. 2d). Half of the stimuli contained a grid, and the other half did not. If the illusion discovered in Experiment 1 is robust, then we should expect the estimated number of dots to be lower when a grid is visible.

3.1. Methods

This experiment is identical to Experiment 1 except as noted below. Fifty new participants were tested online via Prolific.

Rather than comparing two sets of dots side-by-side, participants estimated the number of one set of dots at a time. To make the range of to-be-estimated dots more manageable, we decreased the size of the grid on which the dots were superimposed from a 25 × 25 grid to a 15 × 15 grid. There were 13 possible numbers of dots: 20 through 80 in increments of 5. Half of the trials were composed of only blue dots; half of the trials were composed of blue dots plus grey boxes. There were six distinct instances of the combination of the above features, resulting in a total of 156 trials (13 default number combinations × 2 grid locations [grid on left, grid on right] × 6 unique instances). The stimuli appeared for 1s,[2] after which time participants were allowed to indicate the number of dots they had seen by typing in a number. Only inputs of two digits were accepted. If a participant attempted to input a non-two-digit number, they were told to retry with a two-digit number. Participants had unlimited time to respond.

3.2. Results and discussion

The results of Experiment 2 can be seen in Fig. 2e,f. As is evident from the figures, participants tended to indicate there were more dots in the stimuli *without* the grid compared to stimuli *with* the grid ($M = 3.43$, $SD = 3.04$; $t(49) = 7.98$, $p < .001$, d = 1.13) across all base numbers. 45 out of the 50 participants had greater average estimations for the stimuli without the grid (binomial test, $p < .001$). Thus, these results provide converging evidence with Experiment 1 that the presence of empty cells in a grid robustly decreases perceived number.

4. Experiment 3: A full crowd (comparison)

The first two experiments establish a robust illusion of number: For some reason, people tend to underestimate the number of dots in sparse "crowds." Formulated this way, this finding may not be so surprising. Perhaps people underestimate the number of dots in the grid displays because the presence of extra visual information makes it harder to visually attend to the blue dots. Here, we test a different explanation—that people's number estimates are not absolute, but relative. On this view, the reason for the underestimation observed in Experiments 1 and 2 is that the visual system is estimating the number of blue dots to be *relatively* small, compared to the number of unfilled "seats." If this is true, then perhaps the number of dots would be overestimated if the crowd was "full." Here, we tested this prediction by using stimuli like those in Experiment 1 except that over 50% of the available cells in the display were filled by the blue dots (see Fig. 2g).

4.1. Methods

This experiment was conducted identical to Experiment 1 except as noted. Fifty new participants were tested online via Prolific.

So that the blue dots would occupy more than 50% of the available "cells" in the display, a 12 × 12 grid was used instead of a 25 × 25 grid. (This way the number comparisons themselves were comparable to those of Experiment 1, but the proportion of occupied cells was substantially higher.) There were 10 possible default number combinations (left stimulus, right stimulus): [85,125],[100,125],[115,125],[125,125],[125,125],[125,125],[125,125],[125,115],[125,100],[125,85]. There were six distinct instances of each combination of the above features, resulting in a total of 120 trials (10 default number combinations × 2 grid locations [grid on left, grid on right] × 6 unique instances).

4.2. Results and discussion

The results of Experiment 3 can be seen in Fig. 2h,i. Overall, participants selected the side with the greater number of blue dots 80% of the time, $t(49) = 19.6$, $p < .001$, $d = 2.77$. As is evident from the figures, participants tended to indicate that the side *with* the grid was more numerous ($M = 63.1\%$, $SD = 15.2\%$; $t(49) = 6.09$, $p < .001$, $d = 0.861$). Forty-two out of 50 participants indicated that the side *with* the grid was more numerous more often than not (binomial test, $p < .001$) across all differences in number. The effect was stronger when isolating only trials in which the number of dots was equivalent ($M = 69.3\%$, $SD = 20.5\%$; $t(49) = 6.66$, $p < .001$, $d = 0.942$). Thus, these results indicate a reversal of the effect shown in Experiments 1 and 2. Not only does a large number of empty cells in a grid cause underestimation, but a small number of empty cells (or rather, a large number of full cells) causes an *increase* in perceived number.

It is worth noting, however, that this overestimation effect is not overwhelming in the same way as the underestimation effect documented in Experiments 1 and 2. Whereas the underestimation effect is obviously appreciable in simple displays, the overestimation effect seems to reveal itself only in the data (at least for us). For that reason, we think the overestimation effect should be treated with caution. We have been careful to ensure this effect is empirically robust (see also Experiment 4), yet we still think there must be more to the overestimation effect than meets the eye.

Even so, the fact that the presence of a grid results in a bidirectional effect on number perception silences most concerns about would-be confounds. If aware of only the results of Experiment 1, one may have been tempted to say that the presence of the grids is distracting, preventing participants from seeing the dots and thus resulting in underestimation. Or if aware of only the results of Experiment 3, one may have been tempted to say that participants were conflating the number of dots with the number of overall items. Yet neither of these

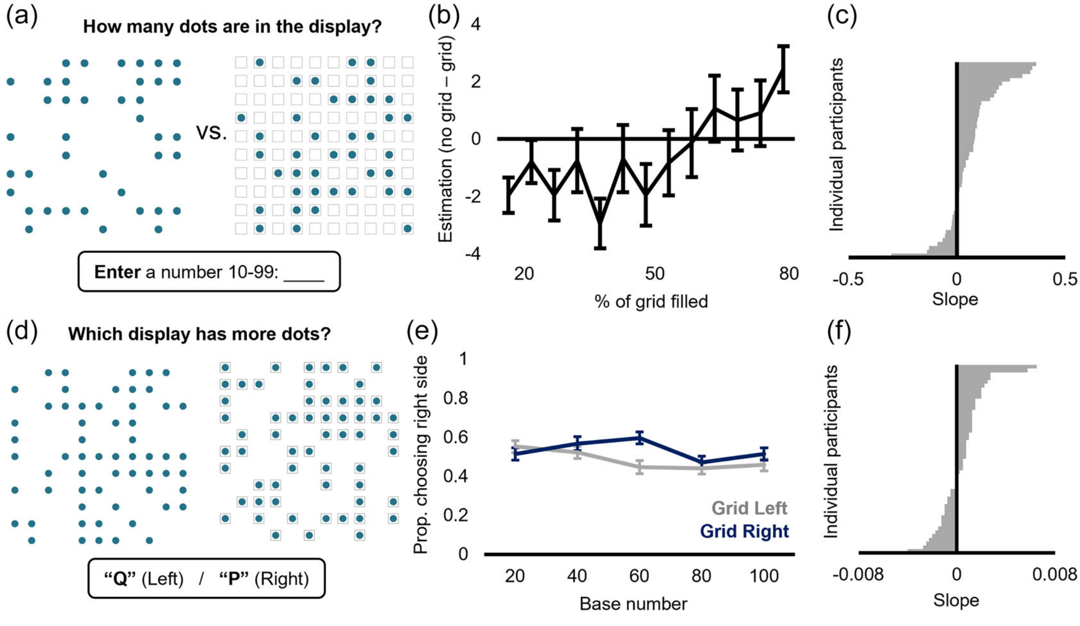

Fig. 3. Example stimuli and design of Experiments 4 and 5. Example displays for each experiment are equal in number. Error bars represent ± 1 *SEM*. (a) In Experiment 4, participants estimated the number of dots arranged in a 10×10 grid. The grid was visible in half the trials. (b) Participants tended to indicate that the side without the grid had more dots when occupancy was below 50% and that the side with the grid had more dots when occupancy was above 50%. (c) Participants tended to have a positive slope, indicating that as occupancy increased, participants increasingly perceived the grid stimuli as more numerous. (d) In Experiment 5, participants compared sets of dots arranged in an 11×11 grid. On each trial, one of the displays had boxes around the dots (but no empty boxes). (e) Participants equally selected the grid and non-grid stimuli. (f) The slope of participant responses indicates that no substantive changes in grid selection occurred as occupancy increased.

explanations could explain both patterns of results. Combined, these results hint at a different explanation: That number is somehow perceived proportional to other relevant information in the visual scene (see Qu, Clarke, Luzzi, & Brannon, 2025). We further probe this possibility in the following experiments.

5. Experiment 4: The "crowd size illusion" (estimation)

In Experiments 1 and 3, we demonstrate opposing crowd size illusions. When "crowds" are relatively empty, perceived number is reduced; when crowds are relatively full, perceived number is increased. However, empty and full crowds were never directly compared, leaving open the possibility that the previous results are explained by some sort of response bias. Here, we asked whether both the "empty" crowd illusion and the "full" crowd illusion would manifest within the same task. We tested this by using an estimation task like Experiment 2, except the stimuli filled anywhere from 20% to 80% of the total available "cells" (see Fig. 3a).

By doing so, we can assess not only whether we observe both effects at the same time but also where in the distribution the effect flips from an "empty" to a "full" crowd illusion.

5.1. Methods

This experiment was conducted identical to Experiment 2 except as noted. Fifty new participants were tested online via Prolific.

A 10 × 10 grid was used instead of a 15 × 15 grid. This way the number of dots present in the grid was equivalent to the percentage of the grid filled. There were 13 possible numbers of dots: 20 through 80 in increments of 5. Half of the trials were composed of only blue dots; half of the trials were composed of blue dots plus grey boxes. There were six distinct instances of the combination of the above features, resulting in a total of 156 trials (13 default number combinations × 2 grid locations [grid on left, grid on right] × 6 unique instances).

5.2. Results and discussion

The results of Experiment 4 can be seen in Fig. 3b. As is evident from the figure, participants tended to indicate that the side *without* the grid had more dots when occupancy was below 50% and that the side *with* the grid had more dots when occupancy was above 50%. This effect was also present within individual participants (see Fig. 3c). Across all trials, 34 out of 50 participants had a positive slope, indicating that the difference between their estimates of grid versus non-grid stimuli increased as the occupancy of the grid increased (binomial test, $p = .008$; $M = -0.06$, $SD = 0.13$; $t(49) = 3.47$, $p < .001$, $d = 0.49$). This indicates that as the occupancy of the grids increased, participants tended to overestimate the grid stimuli more. Per our preregistered analysis plan, we also tested whether the three smallest (20%, 25%, and 30%) and largest (70%, 75%, and 80%) crowd sizes resulted in opposing effects on number estimation. Consistent with the result of Experiment 1, "empty" crowds resulted in underestimation ($M = -1.57$, SD $= 3.58$; $t(49) = 3.09$, $p = .003$, $d = 0.44$), and consistent with the results of Experiment 3, "full" crowds resulted in marginal overestimation ($M = -1.33$, $SD = 4.92$; $t(49) = 1.91$, $p = .06$, $d = 0.27$). The difference between the two sets was significant ($t(49) = 3.13$, $p = .003$, $d = 0.44$). Thus, these results indicate that the crowd size illusion results in robust bidirectional effects—validating the suggestion that number is perceived proportionally.

6. Experiment 5: No empty seats

Our suggestion is that the crowd size illusion is driven by the number of *empty* seats—that filled seats are enumerated *relative* to them. However, in the displays in the previous experiments, they differ not only with respect to the presence of empty seats; they also differ with respect to the presence of filled seats. That is: By adding a grid, we create both "filled" and "empty" seats simultaneously. Here, we isolated the influence of filled and empty seats by effectively removing all empty seats from the display. We had participants compare regular dot displays against displays in which every dot was surrounded by a box (but without any empty boxes). If the crowd size illusion is driven simply by the presence of filled boxes, we should expect to find the same effects as before. If the crowd size illusion is instead about the relative proportion of filled and empty seats, we should expect to find no difference in perceived number.

6.1. Methods

This experiment was conducted identical to Experiment 1 except as noted. Fifty new participants were tested online via Prolific.

In the grid stimuli, the empty boxes are removed so that only the boxes surrounding the dots (i.e., the "full seats") remain. Additionally, the stimuli were changed so that they encompassed both empty and full crowds. To accomplish this, an 11×11 grid was used. Trials could have a base number of either 20, 40, 60, 80, or 100. There was also a multiplier of either 0.85, 1, 1, 1, or 1.15 assigned to each trial, which modified the number of dots on one side of the display. These features were counterbalanced with the side that the modifier was present on and the side that the grid was present on, resulting in 100 trials (5 base numbers $\times$ 5 multipliers $\times$ 2 multiplier locations [multiplier left, multiplier right] $\times$ 2 grid locations [grid left, grid right].

6.2. Results and discussion

The results of Experiment 5 can be seen in Fig. 3e,f. Participants selected the side with the greater number of dots 74% of the time, $t(49) = 11.9$, $p < .001$, $d = 1.69$. Participants' selection of the grid did not differ significantly from chance in the "empty crowd" trials (base numbers 20 and 40; $M = 50.2\%$, $SD = 15.7\%$; $t(49) = 0.07$, $p = .95$, $d = 0.01$) or the "full crowd" trials (base numbers 80 and 100; $M = 52.2\%$, $SD = 16.3\%$; $t(49) = 0.95$, $p = .35$, $d = 0.13$). The empty and full crowd trials also did not differently from each other ($t(49) = 1.23$, $p = .22$, $d = 0.18$). The same effects are found when looking only at trials in which the number of dots were equivalent in the two displays (empty: $M = 49.3\%$, $SD = 17.7\%$; $t(49) = 0.30$, $p = .77$, $d = 0.04$; full: $M = 53.2\%$, $SD = 19.6\%$; $t(49) = 1.14$, $p = .26$, $d = 0.16$; difference: $t(49) = 1.74$, $p = .09$, $d = 0.25$). For each participant, a slope was calculated for the proportion of the time they chose the grid as the occupancy increased (see Fig. 3f). The slopes were not significantly different from 0 ($t(49) = 1.63$, $p = .11$, $d = 0.23$), indicating that there was no change in grid selection as the occupancy of the displays changed.

Evidently, by removing the empty boxes in the grid displays, any effects of the crowd size illusion disappear. This supports the idea that it is not only the presence of an additional object group (in the form of the grid), but the relationship between the grid and the dots that is creating this illusion.

7. General discussion

Here, we have documented a systematic illusion of number perception: the *crowd size illusion*. First, we showed that people *underestimate* the number of individuals in a relatively "empty" crowd (Experiment 1) and that this illusion is robust even in direct estimation tasks (Experiment 2). Then, we showed that this illusion reverses as crowds become increasingly "full" as if the visual system is, to some extent, estimating visual number relative to the proportion of "seats" that are occupied (Experiment 3). In fact, the magnitude of the crowd size illusion scales continuously with the proportion of occupied seats, flipping directions around the 50% mark (Experiment 4). Finally, we showed that the illusion specifically results from the addition of "empty" seats, not just "full" seats (Experiment 5). We also conducted three additional supplemental experiments to rule out even more possible low-level confounds (see the supplementary material on our OSF page). These results collectively establish a novel illusion of number perception, with far-reaching implications for how number perception is understood.

7.1. A robust, see-it-for-yourself illusion

The crowd size illusion is not a social phenomenon; it is a *visual* illusion of number. While some illusions of number perception reveal themselves only through careful data analysis (e.g., DeWind et al., 2020; Yousif, Chen, & Scholl, 2020), the "crowd size illusion" appears to be robust such that it is apparent in simple visual displays. You can see the magnitude of the illusion yourself by investigating Fig. 1. In Experiment 1, we found that even when displays with boxes had almost 50% more dots than the display without boxes, people still chose the display without boxes over 30% of the time (see Fig. 2b). Indeed, this paper was inspired by our experience out in the real world: We consistently found that, despite our best efforts, we had difficulty estimating the number of people in audiences (despite being relatively accurate in other contexts).

One interesting fact about the crowd size illusion is that it describes two distinct illusions in one. On the one hand, you have an "empty crowd illusion" whereby crowds with many empty "seats" are perceived as less numerous. On the other hand, you have a "full crowd illusion" where crowds that fully occupy the available "seats" are perceived as more numerous. The fact that we observed these two opposing effects within the same experiments (Experiment 4) strongly suggests that whatever is happening here is not merely a consequence of any sort of response bias or decision-level process. Indeed, the magnitude of the crowd size illusion scales linearly with the proportion of the available "seats" that are occupied. The direction of the effect reverses at approximately 50% occupancy. These facts seem to support the interpretation that enumeration of the relevant dots occurs *relative to* the other available numerical information (i.e., the total number of "seats").

7.2. What is going on?

There are many illusions of number perception. For example, *regular* patterns of objects appear more numerous than *random* ones (i.e., ones with more sporadic spatial distributions; see Ginsburg, 1976; see also Durgin, 1995). Sets of objects that are *connected* (e.g., via thin lines) are perceived as less numerous than equivalent sets of objects without such connections (Franconeri et al., 2009, He et al., 2009). Sets of objects that are more coherent, visually or semantically, are perceived as more numerous than equivalent but less coherent sets (DeWind et al., 2020; Qu, Bonner, Dewind, & Brannon, 2024). Even more generally, the perception of number is robustly influenced by several other spatial illusions: Sets of dots positioned within Ebbighaus-illusion-inspired arrangements of circles, for instance, vary in their perceived number (Picon et al., 2019).

To explain the crowd size illusion, one may first think to look at the known numerical illusions for inspiration. Is this illusion simply a byproduct of known effects of number perception?

If only the results of Experiments 1 and 2 were on the table, we might be tempted to say that the crowd size illusion is the result of some sort of attentional deficit: If there are more "distracting" items in a display (i.e., the grey boxes which form the grid), the visual system will struggle to attend to the relevant items. This explanation is appealing. After all, we know that there is a direct link between attention (via objecthood) and number estimation (Franconeri et al., 2009; He et al., 2009). Yet this explanation seems less likely to explain the results of Experiments 3 and 4, wherein we demonstrated that a proportionally large crowd is perceived as *greater* in number, despite the potentially distracting added "seats." In other words, it is not the "seats" themselves that cause overestimation or underestimation; it is the relation between the number of audience members and those seats that seems to matter. This is demonstrated most clearly by the *lack* of an illusion when the "empty" seats are removed in Experiment 5. We cannot deny that attention likely plays some role in this phenomenon—as it must, inevitably, in any visual perception task—yet an attentional explanation seems insufficient to explain the full pattern of results observed here.

One might think that the crowd size illusion could also be explained by a more general stimulus parameter, like entropy (see Qu, DeWind, & Brannon, 2022). Insofar as adding irrelevant elements to a display increases its entropy, this could explain the reduction of the number in Experiments 1 and 2. But, again, a more general explanation like this one is always going to struggle to accommodate the fact that the crowd size illusion goes in two opposite directions. Even if entropy explained the underestimation results, it could not explain the overestimation results.

Somewhat relatedly, the crowd size illusion may be explained as a congruity effect between *number* and *proportion*. That is, much like there are well-known congruity effects between *number* and *area* (such that increased area leads to a greater sense of number, and vice versa; see Gebuis, Cohen Kadosh, De Haan, & Henik, 2009; Hurewitz et al., 2006; Nys & Content, 2012; Rousselle, Palmers, & Noël, 2004; Rousselle & Noel, 2008; Walsh, 2003; Yousif & Keil, 2020), the crowd size illusion could be explained as a congruity effect between *number* per se and the *relative* number of "seats" that are "filled." The nice thing about such an explanation is that, unlike many other plausible explanations, it naturally explains the bidirectionality of the effect. This strikes us as a valid way of understanding the crowd size illusion. Indeed, models of proportion estimation predict exactly the same sort of effects (see Gouet, Jin, Naiman, Peña, & Halberda, 2021; Hollands & Dyre, 2000). The other upshot of this framing is that it invokes psychophysical principles that extend far beyond number estimation to include everything from line lengths (Spence, 1990) to spatial position (Huttenlocher, Hedges, & Duncan, 1991; Yousif et al., 2020; Yousif et al., 2024) to time intervals (Nakajima, 1987).

One way of thinking about the bidirectional effects of the crowd size illusion is through models of proportional reasoning. Gouet and colleagues (2021), building on the Cyclical Power Model (Hollands & Dyre, 2000) propose that there are systematic distortions in the perception of proportion, such that there is overestimation for proportions above 0.5 and underestimation for 0.5 (although the reverse does occur). Given that the participant's estimation of number is likely biased by their perception of relative magnitudes like proportion, this model could reasonably predict the bidirectional estimation effects in the crowd size illusion. That is, if the proportion of displays below 50% occupancy is underestimated (and vice versa), it would follow that participants' estimates of number too would be lower.

The crowd size illusion is also related to the idea of numerical autoscaling (Odic et al., 2024), wherein an observer's perception of number is scaled relative to the automatically perceived minimum and maximum value in a display, in that both emphasize the importance of relative coding. Perhaps the grid influences perceived number precisely by providing an anchor of a larger number to compare against. Though this would not explain the bidirectional effects we observe, this possible relationship between the crowd size illusion and autoscaling is one that could be explored further in future work.

Another intriguing possibility is that the switch between an "empty crowd illusion" and a "full crowd illusion" reflects a switch from numerical processing to texture processing (see Anobile, Cicchini, & Burr, 2016; Dakin et al., 2011; Morgan et al., 2014). This is not a possibility that we can rule out entirely. However, there are a few reasons that we disprefer this explanation. One reason is that the switch from underestimation and overestimation seems to happen as a function of the proportion of the grid that is filled, regardless of the number of absolute dots or the space that they occupied. A second reason is that the switch seems to occur right around the 50% mark, which seems to indicate that the qualitative change between being relatively "empty" and relatively "full" is significant. A third reason is that the data themselves do not provide any indication of such a swap: In the estimation task, for instance (Experiment 2), number estimations continuously increase throughout the tested range. Furthermore, the coefficient of variation decreases slightly but continuously throughout the numerical range tested, consistent with other observations (see Testolin & McLelland, 2021). Even so, texture processing may play some role in the processing of these stimuli, and thus this perspective is worth considering in any future investigations of the crowd size illusion.

The most natural explanation of the observed data, in our view, is that number perception is relative: That the estimation of any numerical information is dependent on other local numerical information. Perhaps the crowd size illusion is a sort of "numerical Ebbinghaus illusion." Much like the size of irrelevant, not-to-be-estimated circles influences the size of a target circle (see Fig. 4), the size of irrelevant, not-to-be-estimated numerical information may influence the perceived number of a target set. Both illusions work under roughly the same conditions; both illusions result in phenomenologically compelling demonstrations; and both illusions could perhaps reveal some general truth of magnitude perception—that it is inherently relativistic.

7.3. A challenge to our understanding of number perception?

Picon et al. (2019) contrast two general theories of number encoding: A domain-specific theory, on which number is a primary visual feature which is estimated directly, and a domain-general theory, on which number is perceived indirectly through various non-numerical

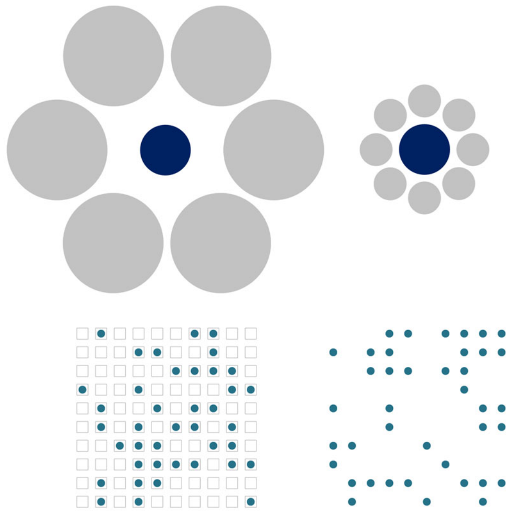

Fig. 4. The Ebbinghaus illusion, in which a central dot looks larger when surrounded by smaller dots, alongside the crowd size illusion. Might we think of the crowd size illusion as a sort of numerical Ebbinghaus illusion?

quantities like size, density, convex hull, and so on (see also Dakin et al., 2011; Gebuis & Reynvoet, 2012a, 2012b; Leibovich et al., 2017). On account of the fact that number discrimination *and* number estimation are influenced by different spatial visual illusions, they argue in support of the domain-general account. The present findings could be viewed as consistent with their view: Here, we have shown that seemingly irrelevant quantity information influences the evaluation of relevant numerical information to a large extent.

While the crowd size illusion is in some respects consistent with this prior work, it is unlikely to be explained simply by confounds with non-numerical dimensions. Unlike other numerical illusions, the crowd size illusion represents a case in which *adding* something to a display *reduces* perceived number (as is also the case with the "connectedness illusion"; see Franconeri et al., 2009, He et al., 2009). The fact that the illusion reverses as a function of the proportion of occupied space further limits the viability of these explanations: The addition of a grid in the display has an opposing effect on perceived number, depending on the relation between the dots and the grid.

Many theories of number perception side-step these issues altogether, focusing not on how number is perceived in context, but on how number is perceived in isolation (e.g., Aliik & Tuulmets, 1991; Cheyette & Piantadosi, 2020). Yet if it is true that the perception of number is inherently relativistic, then we will never understand it with such approaches (just as we cannot explain size perception by appeal to the physical dimensions of objects; see Yousif & Keil, 2019, 2021). We need models that not only succeed in estimating numbers to the same extent that humans do but also ones that fail in the surprising and counterintuitive ways that we do. The exceptions matter. In fact, the exceptions may reveal *more* about the mechanisms of number perception than canonical cases of number perception (see Helmholtz, 1896, via Clarke, Qu, Luzzi, & Brannon, 2025)—because unlike canonical visual number displays, illusions like the crowd size illusion are unlikely to be explained by confounds with properties like density, area, or convex hull. They demonstrate, powerfully, how much of what we see can be influenced by subtle, seemingly irrelevant details.

A provocative recent suggestion is that the approximate number system has a "part–whole" format, meaning that the number of items in a subset is represented relative to a super set (if, e.g., there are multiple different colors of dots in a display; Qu, Clarke, Luzzi, & Brannon, 2025). The current data may be seen as consistent with that possibility, insofar as the parts (i.e., filled seats) are influenced by the perception of the whole crowd (i.e., all the seats). That said, it is also possible that the data reflect a "part-part" format, whereby the filled seats are estimated relative to the empty seats. While the present data do not clearly adjudicate between these two possibilities, we believe there is promise in this *kind* of approach for understanding the format of numerical information. We believe this is a theoretical perspective that warrants additional investigation.

7.4. Constraints on generality

Though the crowd size illusion is phenomenologically compelling, its generality remains unclear. The illusion is robust in the sorts of displays tested here (see also supplemental Experiments 1–3 on our OSF page), but there are many, many other ways one might approach testing the broader theory that we have proposed (i.e., that number estimation is inherently relativistic). We encourage future work that tests the boundary conditions of this phenomenon more thoroughly.

8. Conclusion

The crowd size illusion is notable for at least three key reasons. First, it is striking that *adding* information to a display results in a *decrease* in perceived number (as was the case in Experiments 1, 2, and 4). Such a pattern cannot be explained by a "more-is-more" bias. Second, it is unique that the illusion results in two opposing effects, depending, seemingly, on the proportion of a stimulus that is filled. The fact that the crowd size illusion is bidirectional greatly limits the range of possible explanations. Finally, it is noteworthy that the crowd size illusion is phenomenologically compelling, readily appreciable in simple demonstrations. In these ways, the crowd size illusion points to a gap in the understanding of number perception, while potentially providing support for the nascent view that number perception may depend on part–whole relations.

Notes

1 This analysis in this experiment (as well as all subsequent experiments) was not preregistered but was added based on helpful feedback from an anonymous reviewer.

2 The pre-registration incorrectly stated that the stimuli would appear for 750 ms. They always appeared for 1 s. The same is true for the other estimation task used in Experiment 4.

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