

Volume Estimation Through Mental Simulation



Hannah Perfecto¹, Kristin Donnelly², and Clayton R. Critcher²

¹Olin Business School, Washington University in St. Louis, and ²Haas School of Business, University of California, Berkeley

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Abstract

Although mental simulation underlies many day-to-day judgments, we identified a new domain influenced by simulation: volume estimation. Previous research has identified various ways in which volume estimates are biased but typically has not presented a psychological process by which such judgments are made. Our simulation-informs-perception account proposes that people often estimate a container's size by simulating filling it. First, this produces an orientation effect: The same container is judged larger when right side up than when upside down because of the greater ease of imagining filling an upright container. Second, we identified a cavern effect: Imagining pouring water through a narrow opening toward a relatively wide base produces a sense that the container is cavernous and large (compared with identically sized, wide-topped, narrow-based containers). By testing for and demonstrating the importance of simulation to these effects, we showed how complex perceptual judgments can be distorted by higher level cognitive influences even when they are necessarily informed by modularly processed perceptual input.

Keywords

simulation, judgment, perception, volume estimation, metacognitive ease, open data, open materials

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Humans' capacity for mental simulation assists with a variety of judgments. It helps forecast the future: Grocery shoppers simulate how hungry they will be when determining how much to buy (Gilbert, Gill, & Wilson, 2002). Global warming seems more likely to occur when it is easier to simulate its effects (Risen & Critcher, 2011). Although simulation can offer valid input to judgments, simulations can also be distorted by uninformative states. Hungry shoppers wrongly project their present hunger into the future and overbuy. People in cold rooms have trouble simulating the consequences of a world plagued by global warming and thus err toward climate-change skepticism. Given that people frequently mistake changes in the self for changes in the world (Eibach, Libby, & Gilovich, 2003), it is perhaps unsurprising that people fail to correct for these biases.

More controversially, however, researchers have claimed that mental simulation affects visual perception of the present. People estimate their distance from an object by simulating reaching for it (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009). When assessing

the steepness of a hill, people imagine climbing it (Witt & Proffitt, 2008). Individuals who can jump higher may envision a more reachable and thus shorter world. People wearing heavy backpacks or who have a fear of falling imagine a climb to be more tiring and treacherous and, accordingly, report slopes to be steeper than do people who are less burdened and more energized, who report slopes to be shallower (Proffitt, 2006; Proffitt, Stefanucci, Banton, & Epstein, 2003; Stefanucci, Proffitt, Clore, & Parekh, 2008).

Although simulation is necessary to consider and judge the future, the idea that cognitive processes can exert a top-down influence on visual perception has come under recent scrutiny (Firestone, 2013; Firestone & Scholl, 2016). After all, a hallmark of visual processing is modularity, meaning that it should be immune to

Corresponding Author:

Hannah Perfecto, Washington University in St. Louis, One Brookings Dr., St. Louis, MO 63130
E-mail: perfecto@wustl.edu

cognitive interference (Fodor, 1983; Pylyshyn, 1999). Indeed, Firestone and Scholl (2014) showed that many supposedly top-down effects on perception are ultimately attributable to artifactual characteristics (see also Durgin, Klein, Spiegel, Strawser, & Williams, 2012).

In the present article, we do not claim to settle this debate but, rather, demonstrate how cognition plays a crucial and distorting role in translating perceptual input into more complex perceptual judgments. Consider volume perception. Although we perceive size, seeing volume is less direct than the single dimensions that inform it (e.g., height). Instead, volume perception requires people to translate perceptual inputs into a perceptual judgment. This can be done formally (i.e., with rulers, geometry textbooks, and calculators). But in practice, people approach such perceptions more intuitively; one rarely observes, for example, coffee shop patrons using measurement instrumentation when choosing a cup size. Previous research has identified how salient features (e.g., elongated height) exert disproportionate influence on volume perception (Yang & Raghbir, 2005). However, this literature largely provides “as-if models” (Ordabayeva & Chandon, 2013), algorithms that can anticipate specific sources of judgment error but make no predictions about the process by which those perceptual judgments are made.

We begin closing this gap by proposing mental simulation as a cognitive process that helps convert modularly processed, perceptual input into perceptual judgments of volume. To estimate a receptacle’s volume, people often simulate how much they could pour into it. Pouring happens with the flow of gravity (from opening to base) into an upright container. Our simulation-informs-perception (SIP) account leans on this simple property to inform two novel hypotheses of how simulation may lead volume perception astray.

First, we hypothesize an *orientation effect*: A container will seem larger when right side up than upside down. We suggest that this is because it is easier to imagine filling a right-side-up container than an upside-down one; the metacognitive ease of this simulation contributes positively to the subjective judgment of its size. By analogy, if home buyers find it hard to simulate fitting their furniture in a room, that room may seem smaller.

Second, we posit a *cavern effect*. Because one fills a container by pouring liquid through its opening to reach its base, a low top-to-base ratio will create a sense that a container is large and cavernous. That is, imagining liquid descending through a narrow top toward a relatively wide, open base may present a stark contrast that offers the subjective sense of filling a vast space. In the present experiments, we tested for both effects, determined whether these effects are driven by

simulation (instead of responses to or misinterpretations of targets’ low-level features), assessed whether subjective ease of simulation produces the orientation effect, and pinpointed whether it is indeed a low opening-to-base ratio that produces the cavern effect.

Experiment 1

Experiment 1 tested the orientation and cavern hypotheses. We predicted that the same container would be judged larger when right side up than upside down (the orientation hypothesis) and that containers with small top-to-base ratios would seem larger than identically sized receptacles with large top-to-base ratios (the cavern hypothesis). We tested these effects’ robustness in two ways. First, we varied whether we explicitly instructed participants to simulate filling the cups in estimating their volume. Second, we varied whether we adopted realistic shading conditions (assuming an overhead light source) or invariant shading (to keep more equivalent bottom-up features of upright and inverted targets).

Method

Sample-size determination. Our central goal in recruiting participants was to achieve large sample sizes. Toward this end, we wished to collect data simultaneously from both a university subject pool and Amazon Mechanical Turk (MTurk) in all experiments. Because Experiment 1 was conducted when the subject pool was not open, we collected data from MTurk only. We compensated by deviating from the rules described below and recruiting twice as many participants from that source as we would have otherwise.

The sample size on MTurk was determined by (a) the funding lab’s total budgeted funds for MTurk for a particular month and (b) how many other experiments the lab was running on MTurk that month. For experiments conducted in the lab, the sample size was determined by how many participants our research assistants could recruit before the end of an academic semester. This approach allowed us to far exceed the sample size of 50 participants per cell, which Simmons, Nelson, and Simonsohn (2013) suggested as a rough minimum below which a chosen sample size would require additional justification. We also used, when feasible, within-subjects designs that grant additional statistical power. Although we discuss all manipulations, exclusions, and hypothesis-relevant measures in the main text, we invite interested readers to consult the Supplemental Material available online for discussion of three additional measures (one exploring participants’ memory for stimuli in Experiments 2–4 and two assessing self-reported compliance with instructions in Experiment 4). The full

materials and data for each experiment are available online at <https://osf.io/4exy7/>.

Participants and design. Four hundred eighty participants took part in Experiment 1. Each participant was randomly assigned to one of four conditions in a 2 (simulation: fill or no instructions) \times 2 (shading: realistic or invariant) between-subjects design. On 44 of 14,928 total trials (0.29%), participants indicated that a cup had no volume. In 42 of 44 such cases, participants were judging an upside-down cup. These participants most likely thought that these were trick questions (“An upside-down cup cannot hold any liquid!”). Because inclusions of these trials would artificially promote hypothesis-consistent results, we excluded them from this and all experiments.

Materials. We created the target cups using SketchUp Pro (Version 17.2.2554; Trimble, 2017), an architecture design program that allowed for the creation of shapes under various lighting conditions. Cups were four sizes (tiny, small, large, or huge). For each cup size, we created cups that took one of three shapes. These shapes were defined by their top-to-base ratio, that is, the ratio of the aperture’s diameter to the base’s diameter. Wide-based cups had a low ratio (1:3). Cylinders had a ratio of 1:1. Wide-topped cups had a high ratio (3:1). Example stimuli in these three shapes are depicted in the left, middle, and right columns, respectively, of Figure 1.

For each cup, we created a version that was right side up as well as two versions (one for each shading condition) that were upside down. SketchUp permits shapes to be shown under specified environmental lighting conditions, as though they were outside and illuminated by the sun. The program requires specification of an orientation (e.g., northwest facing), a date (e.g., June 27), a time (e.g., 2:30 p.m.), and a location (e.g., Boulder, Colorado). The cup’s upright or inverted orientation was demonstrated most clearly by the upright or inverted orientation of the brand name on the container, Agua Perfecto. For inverted cups created under conditions of invariant shading, the upside-down cup image was merely a 180° rotation of the right-side-up image (see Fig. 1). This made the upright and inverted images more parallel in terms of their bottom-up features. For inverted cups created under realistic shading (see Fig. 1), the upside-down cup was reshaded to match the lighting parameters specified earlier. On the one hand, invariant shading offers the more conservative test. It avoids the problem that shading differences that are confounded with orientation, as opposed to the orientation itself, might otherwise explain our effects. On the other hand, making certain that our effects are robust even under naturalistic shading conditions minimizes the worry that ecologically invalid shading cues lead participants to draw misguided inferences about the shape (e.g.,

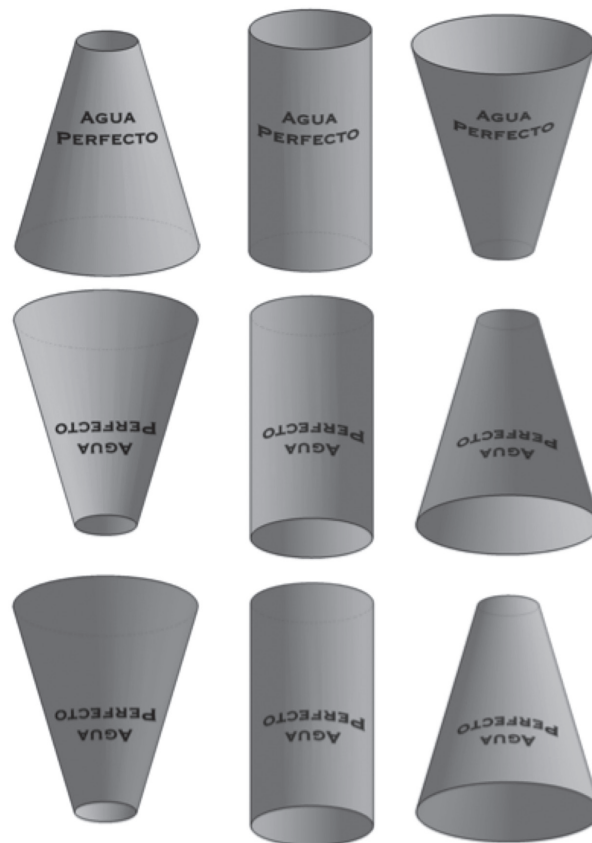


Fig. 1. Sample stimuli for Experiment 1. Targets varied by shape: wide based (left column), cylindrical (middle column), and wide topped (right column). Targets also varied by orientation and shading: right side up (top row), upside down with invariant shading (middle row), and upside down with realistic shading (bottom row).

convexity) of the images (Moore & Cavanagh, 1998; Yonas, Kuskowski, & Sternfels, 1979).

Procedure. Participants estimated the volume of 24 cups, each displayed on a computer screen. Familiarity with cup sizes in a typical metric, such as ounces or milliliters, might constrain participants’ willingness to report their actual perception of nuanced differences in size. Guided by this concern, we introduced a fictitious unit of measurement for this and the remaining experiments: *xids*. We first displayed an exemplar (referred to here as a “modulus”) that helped participants get a sense of scale (Raghubir & Krishna, 1999). Before each trial, participants saw an image of an upright cylinder that was said to be 16 *xids*. If people estimate volume by imagining how much they could pour into a container, they must have some known quantity from which this pouring occurs (e.g., “I can imagine easily pouring all 16 *xids* into that cup”). This modulus was larger than the tiny and small cups but smaller than the large and huge cups.

Participants in the fill condition were asked to imagine “filling this empty cup all the way to the brim.” Their

volume estimation was probed with, “How many xids of water did you pour into it?” In the no-instructions condition, participants were not asked to simulate filling up the cup. Instead, they were merely asked, “How many xids can this cup hold?” Participants responded to these questions on a slider scale that ranged from 0 xids to 32 xids. The slider defaulted to 16 xids (the size of the modulus) and permitted responses in 10th-xid increments. The 24 cups appeared in random order.

At the end of the experiment, we asked participants to indicate whether they had inklings of what the hypotheses were while completing the study. Participants who indicated that they did were asked to specify what they thought the experimenter was studying and predicting. Only 1 participant articulated the orientation hypothesis, and none articulated the cavern hypothesis. In the Supplemental Material, we detail how the results are robust to using an even more liberal exclusion criterion—removing from analyses anyone who even mentioned thinking that the researchers suspected that orientation or shape might in some way influence or bias his or her volume estimates. In combination, this makes it extremely unlikely that the results reported below are merely reflections of experimenter demand.

Results

Because some participants had missing data (because they indicated that a cup’s size was 0 xids, skipped an item, or exited the experiment early), we opted to use multilevel modeling instead of a mixed-model analysis of variance. We defined two Level 1 variables: orientation and shape. Orientation differentiated trials for which a cup was depicted right side up (+1) or upside down (−1). Shape distinguished between wide-based (+1), cylindrical (0), and wide-topped (−1) cups. We nested both orientation and shape within participants in a random-slope, random-intercept model. This permitted the effects of both variables to vary for each participant (random slope) and accounted for differences between participants in how much they tended to see targets as larger or smaller (random intercept). Both of our between-subjects manipulations were modeled as Level 2 variables. The shading variable distinguished participants who were exposed to cups under realistic (+1) or invariant (−1) shading conditions. The simulation variable identified participants who were explicitly asked to simulate (+1) filling the cup or given no instructions (−1) for how to estimate its volume. We included all interactions that could be made from the four predictors. Finally, we included a random effect of cup, which identified each trial in terms of the size of the depicted cup.

We present the descriptive results in this and every experiment using three rules. First, all means presented are predicted values from the relevant mixed model.

Second, we present results on the size of the cavern and orientation effects by presenting the difference in judged size of right-side-up and upside-down containers (orientation effect) or wide-based and wide-topped containers (cavern effect). Third, there are complexities in capturing uncertainty in point estimates when they characterize data affected by both between-subjects and within-subjects sources of variation (see Masson & Loftus, 2003). To capture uncertainty in our effects, we adapted recommendations of Franz and Loftus (2012) by presenting the 95% confidence intervals (CIs) for the orientation and cavern effects (i.e., differences between two point estimates) whenever they are discussed.

Orientation effect. We observed a main effect of orientation, $t(9510.10) = 3.15$, $p = .002$. Consistent with the orientation hypothesis, results showed that participants judged the same cups to be larger when they were shown right side up ($M = 16.94$ xids) than upside down ($M = 16.73$ xids), orientation effect = 0.21, 95% CI = [0.08, 0.35]. Neither the Orientation × Simulation nor the Orientation × Shading interactions approached significance, $ts < 1$. In other words, the orientation effect was quite robust: We found no evidence that it changes in the presence or absence of simulation instructions or realistic shading.

Cavern effect. To assess the cavern hypothesis, we restricted our analysis to the 16 (of 24) cups with a wide top or wide base. It is worth reinforcing that because we varied the orientation and the shape orthogonally, the specific shape depicted on the screen took one of two rough forms—a truncated cone with one circular end three times the diameter of the other. The inclusion of the brand label reinforced the conceptual understanding of each container’s shape—whether it would be filled by pouring liquid through a narrow top into a wide base (the low top-to-base ratio hypothesized to produce the cavernous illusion that underlies the cavern effect) or whether it would be filled by pouring liquid through a wide top into a narrow base.

As hypothesized, we observed a main effect of shape, $t(397.47) = 5.43$, $p < .001$. Demonstrating the cavern effect, results showed that cups appeared larger when they had a narrow opening and a wide base ($M = 16.75$ xids) than when they had a narrow base and a wide opening ($M = 16.27$ xids), cavern effect = 0.48, 95% CI = [0.31, 0.65]. As with the orientation effect, the cavern effect was robust to our between-subjects manipulations. Neither the instructions to simulate nor the shading conditions moderated the size of the effect, $ts < 1.14$, $ps > .256$.

Having demonstrated that both the orientation and cavern effects emerge under realistic and invariant shading conditions, we proceeded in our remaining experiments to always keep shading invariant. This

offers the most conservative test of our hypotheses, especially with the knowledge from Experiment 1 that the basic effects are robust to ecologically valid lighting and shading confounds. We continued to use digitally created target images in our remaining experiments, given that they afforded maximum control over the stimuli's specifications. With that said, Experiment S1 in the Supplemental Material offers additional assurance of the robustness of the orientation effect: It was replicated using right-side-up or upside-down pictures of actual cups.

Experiment 2

In Experiment 2, beyond attempting to replicate the orientation and cavern effects, we tested whether they do indeed result from simulation. To complement the fill condition also used in Experiment 1, we added an empty condition. These participants saw the container filled to the brim. They were asked how much would be poured out if the cup were entirely emptied. In this empty condition, the conditions we thought would give rise to our two effects (the ease of imagining pouring liquid into an upright cup through a narrow opening toward a wide base) would not hold. Thus, we expected the orientation and cavern effects to be reduced or eliminated. This would demonstrate the importance of simulation to our effects. Also, finding evidence of such moderation would show that the orientation and cavern

effects do not simply stem from the inherently difficult task of translating 2-D stimuli into 3-D representations (e.g., Albert & Tse, 2000).

Method

Participants and design. Two hundred fifty participants took part in Experiment 2. Each participant was randomly assigned to one of two simulation conditions: fill or empty. We excluded 7 of the 6,006 (0.12%) responses because the participant made an estimate of zero volume. In all 7 cases, the target cup was upside down, and the participant was in the empty condition. In other words, these participants seemed to be indicating that nothing could be held inside an upside-down cup; hence, nothing could be poured out.

Materials. Cup stimuli were generated by creating containers that reflected every combination of four factors. Three of these factors defined the cups themselves: color (blue or green), size (small or large), and shape (wide based, wide topped, cylindrical). The image was merely rotated 180° (as in the invariant-shading condition in Experiment 1) to vary the fourth factor, orientation. Although the brand label was different in Experiment 2 (Crystal Lakes), target orientation (and by extension, shape) was again most clearly reflected in the orientation of the label's writing. The volume of the large cup was approximately 2.7 times that of the small cup (see Fig. 2).

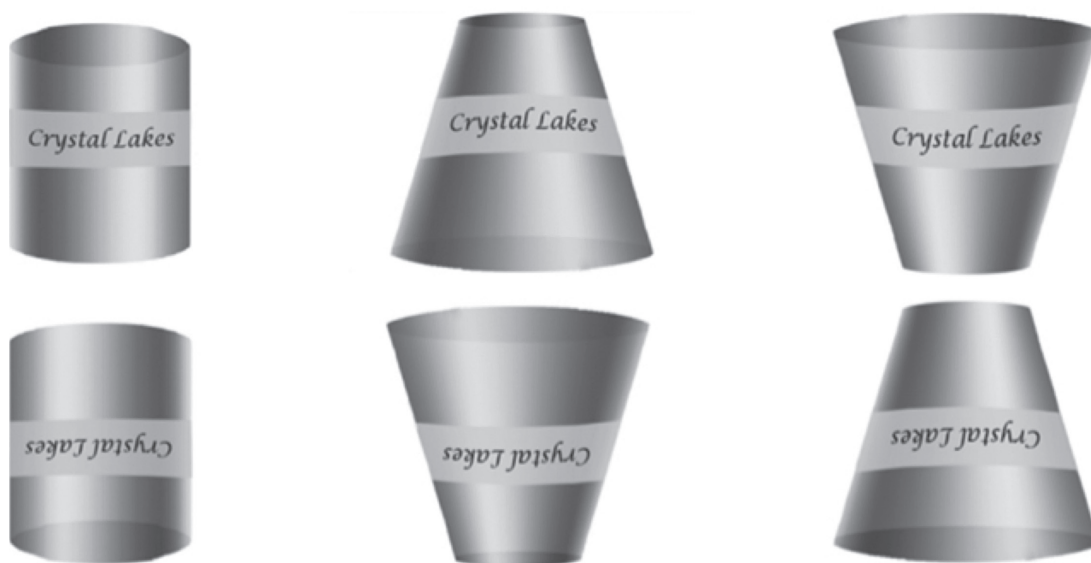


Fig. 2. Sample stimuli for Experiment 2: right-side-up (top row) and upside-down (bottom row) cylindrical (left column), wide-based (middle column), and wide-topped (right column) cups.

Procedure. Once again, participants were asked to estimate the volume of 24 digitally generated cups. As in Experiment 1, each trial began with the presentation of a modulus to remind participants of the scale. In this case, the modulus container was always said to be 15 xids. On each trial, participants adjusted from 15 xids along a slider scale to arrive at their final volume estimates. The allowable response range was 0 to 30 xids, in 10th-xid increments. In the fill condition, participants were asked to “imagine filling this empty cup all the way to the brim.” In the empty condition, participants were instead asked to imagine pouring all of the liquid out of the cup, “which is currently filled all the way to the brim.” Once again, the 24 target stimuli were presented in a random sequence.

Results

We followed a very similar analytic approach to that taken in Experiment 1. First, we defined two Level 1 variables: orientation and shape. Orientation differentiated cups that were depicted right side up (+1) or upside down (−1). Shape instead differentiated cups that were wide based (+1), cylindrical (0), or wide topped (−1). Both shape and orientation were nested within participants in a random-slope, random-intercept model. This permitted the effect of each factor to vary by participant (random slope) and accounted for differences between participants in how they used the xid scale (random intercept).

We defined simulation as the Level 2 variable, which distinguished participants who were asked to estimate volume through a mental simulation of filling a cup (+1) from those who were asked how much they could empty from the cup (−1). We included the three 2-way interaction terms and one 3-way interaction terms made from crossing the orientation, shape, and simulation variables. Finally, we again included the random effect of cup, which accounted for variance attributable to identically sized cups of the same color.

Orientation effect. We began by assessing whether we replicated the orientation effect, at least when participants were encouraged to estimate volume by simulating filling a container, as opposed to emptying it. Consistent with the SIP account, results showed that the Simulation × Orientation interaction was significant, $t(6023.96) = 4.28$, $p < .001$ (see Fig. 3). When participants were encouraged to estimate volume by imagining filling the cup, the exact same cup was judged to be larger when right side up as opposed to upside down, $t(6016.88) = 6.17$, $p < .001$, orientation effect = 0.86, 95% CI = [0.58, 1.13]. But when volume was estimated by a different simulation—by imagining emptying the cup—the effect of orientation disappeared, $t(6028.62) = 0.35$, $p = .730$, orientation effect = 0.04, 95% CI = [−0.21, 0.30].

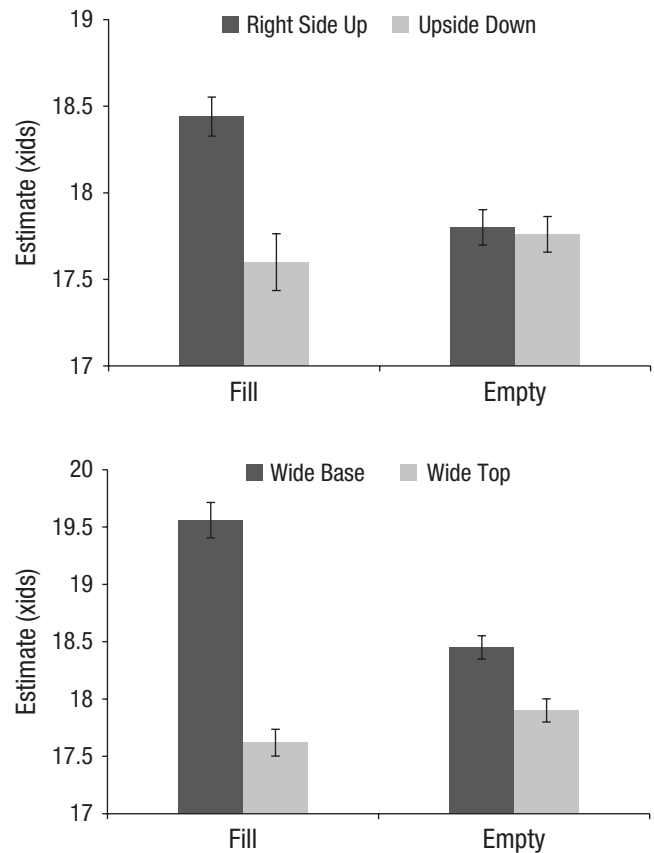


Fig. 3. Results from Experiment 2: mean volume estimate for each simulation condition (fill, empty), separately for cup orientation (top panel) and cup shape (bottom panel). Although the plotted data were predicted from the mixed model, the standard-error bars were calculated from the raw data—accounting for the two random-effects factors—using Morey’s (2008) approach.

Cavern effect. To test the cavern effect, we again restricted our analyses to the 16 (of 24) cups with a wide top or wide base. Once again and consistent with our SIP account, results showed that the cavern effect depended on the nature of the simulation that participants engaged in (see Fig. 3). More specifically, we found a strong Simulation × Shape interaction, $t(4864.20) = 5.70$, $p < .001$. As hypothesized, when participants were imagining filling the cup, they judged the same truncated cone to be larger when the narrow and wide ends were depicted as being the top and base, respectively, than when this pairing was reversed, $t(4874.42) = 10.95$, $p < .001$, cavern effect = 1.93, 95% CI = [1.58, 2.27]. But when the volume was estimated by emptying a cup, the cavern effect was reduced, $t(4847.72) = 3.41$, $p = .001$, cavern effect = 0.56, 95% CI = [0.24, 0.88].

One natural question is whether these effects reflect a distortion in the interpretation of the image. Might the brand label’s orientation change the perceived curvature of the sides? Might the partially occluded wide circle be assumed to be larger when it represents a container’s base instead of its top? Such possibilities—although we

had no reason to suspect them—are distinct from our SIP account that simulation informs complex size perceptions. Yet such concerns highlight the clear value of the simulation manipulation. Even with exposure to the same low-level features, participants instructed to estimate the volume through the simulation of filling, as opposed to emptying, showed stronger orientation and cavern effects. Also, the finding that participants in Experiment 1 who did not receive simulation instructions showed statistically indistinguishable responses from those who were asked to imagine filling the cups is consistent with the possibility that most people employed such simulation spontaneously.

Experiment 3

Experiment 3 explored why the orientation and cavern effects emerge. First, we directly tested whether it is the greater ease of simulating filling a right-side-up container compared with an upside-down container that underlies the orientation effect. Second, we further probed the cavern effect by varying the top-to-base ratio to determine whether the cavern effect is strongest when the base and top are most unequal in size.

Method

Participants and design. One hundred eighty-nine participants took part in Experiment 3. Eight of 4,998 trials (0.16%) were excluded, given estimates of zero xids.

Materials. In this experiment, all cups were the same color: blue. Unlike in our previous experiments, all shapes were truncated cones; no cylinders were included. Furthermore, we varied the size of the small and large ends to produce larger or smaller divergence between the width of the opening and the base. This permitted us to test the role of the top-to-base ratio in the cavern effect. Also, as in Experiment 1, we added dotted lines to depict occluded sections of the cups' bases (see Fig. 4). Participants were reminded of the meaning of the dotted lines on every trial.

For high-divergence cups, the diameters of the top and base were quite different: 4 units and 9 units, respectively (wide based), or 9 units and 4 units, respectively (wide topped). For low-divergence cups, the diameters of the top and base were more similar: 4 units and 6 units (or the reverse) or 6 units and 9 units (or the reverse). In addition to using tops and bases characterized by the same ratio, we designed the stimuli so that both low-divergence cups shared one end in common (either the top or the base) with the high-divergence cup. We modified the height of each container so that all large cups had the same volume; all small cups had the same volume as well. This means the height of the two low-divergence cups straddled that of the high-divergence cup. We review all of these details to demonstrate the care that was taken to minimize the possibility that confounding features could explain the predicted pattern of results.

Procedure. Participants made judgments about 24 computer-generated cups that varied in orientation, shape, and size. The procedure was identical to that of Experiment 2, except that all participants were asked how much they could fit in these empty cups. It was emphasized that we were asking about the maximum amount the container could hold (i.e., that we meant filling the cup to the brim). In addition, after providing each volume estimate, participants indicated the ease of performing the simulation by answering, “To what extent did you find it easy or difficult to mentally simulate filling up the cup?” (1 = *very difficult*, 9 = *very easy*).

Results

We defined four Level 1 variables: orientation, shape, divergence, and height. Orientation differentiated cups that were depicted right side up (+1) or upside down (−1). Shape differentiated cups that were wide based (+1) or wide topped (−1). Divergence distinguished cavernous cups with the greatest difference between their top and base (+2) from the shortest (−1) and tallest (−1) cups—those with tops and bases that were



Fig. 4. Sample stimuli from Experiment 3. Targets varied in top-to-base ratio: 4:6 (left), 6:9 (middle), and 4:9 (right). The left and middle stimuli are low-divergence cups; the right stimulus is a high-divergence cup.

more similar in size. We also included height, a predictor that created an orthogonal contrast to divergence but that distinguished between the three unique shapes of cup: the tallest cup (+1), the middle-height cup (0), and the shortest cup (−1).

All four Level 1 variables were nested within participants in a random-slope, random-intercept model. This permitted the effect of each factor to vary by participant (random slope) and accounted for differences between participants in whether they tended to see all cups as generally larger or smaller (random intercept). We included two 2-way interactions: Shape × Divergence, given its importance to testing our explanation of the cavern hypothesis, and Shape × Height, given that height is the orthogonal contrast to divergence. Finally, we included the random effect of cup used in each experiment. In the two sections below, we focus on different terms in the model to test the orientation and cavern effects.

Orientation effect. First, we investigated the orientation hypothesis. As in the previous experiments, we found that there was indeed a main effect of orientation on volume estimates, $t(5485.31) = 4.02$, $p < .001$. Once again, participants judged the same cup to be larger when it was right side up ($M = 16.51$ xids) as opposed to upside down ($M = 16.03$ xids), orientation effect = 0.48, 95% CI = [0.25, 0.72].

To extend beyond this replication, we examined whether the ease of simulation explained the orientation effect. When predicting simulation ease with the same model, we found a main effect of orientation, $t(158.20) = 3.99$, $p < .001$. As expected, participants reported that it was simpler to imagine filling the right-side-up cup ($M = 5.63$) than the upside-down one ($M = 5.47$), 95% CI for the mean difference = [0.08, 0.25]. When we included simulation ease in our original model, we found that ease of simulation was positively related to volume estimates, $t(115.82) = 4.46$, $p < .001$. The effect of orientation was reduced but still significant, $t(5377.61) = 3.69$, $p < .001$, orientation effect = 0.43, 95% CI = [0.20, 0.67]. These results are consistent with simulation ease partially mediating orientation's effects on volume estimates, $z = 2.97$, $p = .003$. In short, the same cup was judged larger right side up than upside down in part because it is easier to simulate filling it up. In Experiment S2 in the Supplemental Material, we replicated this partial mediation model using the realistically shaded cups from Experiment 1.

Cavern effect. We proceeded to investigate whether the cavern effect—the tendency to judge the same container as larger when people see the base as large and the

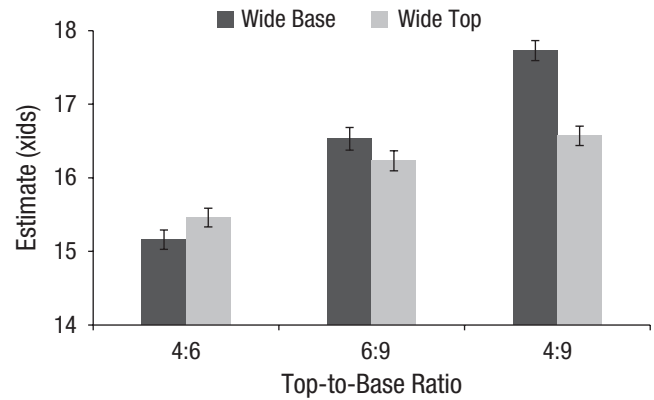


Fig. 5. Results from Experiment 3: mean volume estimate for each combination of top-to-base ratio and cup shape. Although the plotted data were predicted from the mixed model, the standard-error bars were calculated from the raw data—accounting for the two random-effects factors—using Morey's (2008) approach.

opening as small—depends on the difference between the size of the top and the base. Replicating Experiment 2, analyses revealed a main effect of shape that shows that we did observe a cavern effect overall, $t(5203.78) = 2.99$, $p = .003$. However, consistent with our central predictions, results showed a significant Shape × Divergence interaction, $t(4374.89) = 4.28$, $p < .001$. This demonstrated that the cavern effect emerged only when the top and base were sufficiently divergent (4:9, 9:4), $t(1544.04) = 4.82$, $p < .001$, cavern effect = 1.06, 95% CI = [0.63, 1.49]. The cavern effect did not emerge when the divergence was smaller, regardless of whether we examined the short cups (6:9, 9:6), $t(1434.39) = 1.75$, $p = .081$, cavern effect = 0.31, 95% CI = [−0.04, 0.65], or the tall cups (4:6, 6:4), $t(1563.79) = -1.40$, $p = .162$, cavern effect = −0.29, 95% CI = [−0.70, −0.12]. These effects, as well as a theoretically irrelevant main effect of height (a proxy for shape), are depicted in Figure 5.

Our explanation of the cavern effect is not that it is easier to imagine filling up cups with low top-to-base ratios. Instead, we have emphasized that the contrast between the narrow opening that people imagine pouring liquid into and the relatively vast base produces a cavernous illusion. Showing that ease of simulation did not also account for the cavern effect (as it did for the orientation effect), we found no evidence of the same Shape × Divergence interaction on ease of simulation that we found on volume estimation, $t < 1$.

Experiment 4

Although Experiment 3 demonstrated that a relatively large discrepancy between a top and base was necessary for the cavern effect to emerge, the experiment confounded the shape of the cup with the ratio of the opening (through which one would fill the container)



Fig. 6. Sample stimuli for Experiment 4: a lidded (left) and open (right) cup.

to the base. For example, the high-divergence cup—the only one that produced a cavern effect—was also the cup with the most shallowly sloping sides (a consequence of the large discrepancy between the top and the base). To provide a more precise test of our account, we manipulated the size of the containers' top independently of the size of the opening in Experiment 4. Some participants saw open cups—similar to those seen before—in which the opening was the entirety of the top. But other participants saw lidded cups with tops covered except for a narrow hole that served as the opening. Lids narrowed the opening of all cups, regardless of their shape; thus, they should have disrupted the cavern effect. This would further establish the key role of simulation in producing our effects.

Method

Participants and design. Three hundred sixty-four participants took part in Experiment 4. Each participant was randomly assigned to judge cups that were open (as before) or lidded. On 10 of the 8,307 trials (0.12%) for which participants offered a volume estimate, participants made an estimate of zero xids. As before, these trials were excluded.

Materials and procedure. We generated six cup sizes (volume = 7.5 xids, 10 xids, 12.5 xids, 17.5 xids, 20 xids, and 22.5 xids). For wide-topped and wide-based cups, the top-to-base ratio was 4:9 and 9:4, respectively—the ratios that Experiment 3 showed were sufficiently divergent to produce the cavern effect. Half of participants saw open cups without lids: These had entirely open, black tops (see Fig. 6). Participants who saw open cups were told, “Imagine pouring water through the open top, filling this empty cup all the way to the brim.” The other half of participants saw the same cups that had lids with a small opening in the center, indicated by a small black circle. These participants were told, “Imagine pouring water through the small opening on top, filling this empty cup all the way to the brim.” Participants completed 12 trials in random order, each consisting of viewing a

modulus cylinder of 15 xids before estimating the volume of the target cup in xids.

Results

We defined one Level 1 variable: shape. As in Experiment 1, shape differentiated cups with a wide base (+1) or wide top (−1). We defined a Level 2 variable, opening, which distinguished participants who saw cups with open tops (+1) or lidded tops (−1). The Level 1 variable was nested within participants in a random-slope, random-intercept model. This permitted the effect of each factor to vary by participant (random slope) and accounted for differences between participants in the extent to which they saw all cups as generally bigger or smaller (random intercept). We included the 2-way interaction of shape and opening that was crucial for testing our primary hypothesis. Finally, we included the random effect of cup. In this experiment, this was merely a proxy for size.

We observed a significant Base × Opening interaction, $t(7249.49) = 2.85$, $p = .004$ (see Fig. 7), which supports our central hypothesis. For open cups, we replicated the cavern effect, $t(786.98) = 2.66$, $p = .008$,

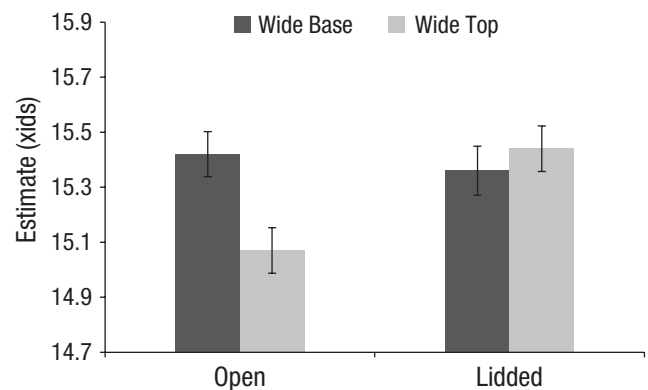


Fig. 7. Results from Experiment 4: mean volume estimate for each combination of cup opening and cup shape. Although the plotted data were predicted from the mixed model, the standard-error bars were calculated from the raw data—accounting for the two random-effects factors—using Morey’s (2008) approach.

cavern effect = 0.21, 95% CI = [0.07, 0.36]. But on lidded trials, when participants imagined pouring water through a tiny opening for all cups, the cavern effect disappeared, $t(786.81) = -0.65$, $p = .513$, cavern effect = -0.08 , 95% CI = $[-0.34, 0.17]$. Note that the absence of a cavern effect in the lidded cups was due to the narrow opening increasing the perceived volume of the wide-topped cups. Only our SIP account, not one based merely on shape, could predict this specific outcome.

Although this experiment further illustrates the key role that simulation (instead of the container's shape) plays in the cavern effect, we concede that these experiments have yet to show precisely why simulation has that effect. We argue that simulating filling a container guides perceivers' attention first to the opening and then to the base. But if this logic is true, then an intervention that leads people to process a base before an opening (in opposition to what simulated filling would naturally prompt) should reverse the cavern effect. Experiment S3 in the Supplemental Material provides this test: Leading participants to attend to the narrow end before the wide end of a cup, as opposed to the reverse, inflates the perceived volume of the container, regardless of which end is the true opening or base.

General Discussion

Four experiments support the hypothesis that simulation informs perception: People will judge a container's volume by simulating how much they can fit in it. This approach helped identify two nonnormative influences on volume estimation. First, a right-side-up cup was judged to be larger than the same one turned upside down (Experiments 1–3). Second, the same container was judged to be larger when its narrow end was shown to be its top, and its wide end was shown to be its base (Experiments 1–4). These orientation and cavern effects emerged when targets were presented under ecologically valid shading conditions or in a more bottom-up equivalent manner (Experiment 1).

These effects appeared regardless of whether participants were explicitly instructed to simulate filling the cup or merely asked for its volume (Experiment 1). But these effects were diminished or eliminated when participants were asked to conduct the opposite simulation of how much could be emptied from the cups (Experiment 2). In combination, this supports that simulation, as opposed to distorted interpretation of targets' low-level features, underlies our effects and that such simulations are employed spontaneously when estimating volume. The orientation effect resulted from the greater ease of simulating filling the right-side-up cup compared with the upside-down cup (Experiment 3). The cavern effect emerged because of the sufficiently

large divergence between the narrow opening (through which filling happens) and the relatively wide base (Experiments 3 and 4).

If simulation does inform perception, does this suggest that features beyond those of the targets themselves (e.g., orientation, top-to-base ratio) should affect volume estimates? One aspect of our paradigms that has not been focal but is presumably essential to the simulation is the modulus. The modulus allows people to simulate pouring water from a container of known volume into one of unknown volume. For example, one might ask, "Could I pour this whole 500 mL bottle of water into that glass?" Although it is hard to imagine pouring water into an upside-down container, it is presumably also unusual to imagine this transfer from a modulus that is itself upside down. That is, the laws of gravity would naturally demand orchestrating a transfer from one right-side-up container to another. Indeed, Experiment S4 in the Supplemental Material found that when the modulus is upside down, it is no longer easier to imagine filling up a right-side-up container compared with an upside-down container. As a result, the orientation effect disappears. Future research may identify other factors that influence simulation ease (e.g., the modulus' shape) and also examine whether simulation is itself cognitively effortful or relatively effortless.

Although Experiment 1 suggested that people spontaneously use simulation in estimating volume, would this always be the case? It was presumably crucial that our participants estimated the volume of receptacles. One can fill a rectangular box but not a rectangular brick. This suggests a logical limit on the SIP account's reach. But even for some receptacles, people may be more likely to ask how much one could pour from them—a simulation that Experiment 2 suggested reduces or eliminates our effects—instead of into them. For example, in estimating the size of a barrel of wine, one might simulate how many glasses it could dispense. Note that such volume perceptions would still involve simulation, but simulations that may evoke a different set of biases from those explored here. In this sense, the SIP account is a guiding idea that may encourage the identification of additional biases through a more thoughtful consideration of how perceptual judgments are made.

The current approach represents a significant departure from past research not merely on volume estimation but also on simulated judgment. We identified a feature of the judgment target, not an ephemeral state of the perceiver (e.g., thirst; Balcetis & Dunning, 2006), that affects simulation. This may make the present phenomena easier to anticipate in natural settings.

Unlike with past research on errors in volume estimation, we did not identify invalid algorithms that lead

size evaluations astray but instead tested how a cognitive procedure that underlies perceptual judgments produces predictable distortions. Most centrally, we emphasize how the cognitive process of mental simulation influences perceptual judgments of volume. Note, though, that we do not assert that cognitive processes exert a top-down influence on perception. Our claim is less radical—that cognition is often the bridge between modular low-level perception and more complex perceptions. Firestone and Scholl (2016) argued that “easily, the most natural and robust distinction between types of mental processes is that between perception and cognition” (p. 1). The present article serves as one model for how these two distinct systems can still be intertwined, with perceptual input informing cognitive procedures that guide more complex perceptions.

Action Editor

Marc J. Buehner served as action editor for this article.

Author Contributions

H. Perfecto and C. R. Critcher developed the idea for the study. K. Donnelly and C. R. Critcher developed, ran, and analyzed the data from Experiment 1 and Experiment S2. Experiments 2 through 4 and Experiment S4 were developed and run by H. Perfecto and C. R. Critcher. K. Donnelly and C. R. Critcher analyzed the data from Experiments 2 through 4, and H. Perfecto and C. R. Critcher analyzed the data from Experiment S4. Experiment S1 was developed and run by C. R. Critcher, who also analyzed the data, and Experiment S3 was developed and run by H. Perfecto and C. R. Critcher, with C. R. Critcher analyzing the data. H. Perfecto and C. R. Critcher drafted the manuscript, providing critical edits to each other's writing. All the authors worked on various aspects of the final revision and approved the final manuscript for submission.

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The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Supplemental Material

Additional supporting information can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797618813319>

Open Practices



All data and materials have been made publicly available via the Open Science Framework and can be accessed at <https://osf.io/4exy7>. Design and analysis plans for the experiments were not preregistered. The complete Open Practices Disclosure for this article can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797618813319>. This article has received the

badges for Open Data and Open Materials. More information about the Open Practices badges can be found at <http://www.psychologicalscience.org/publications/badges>.

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