



The haptic cues humans use to sense small numbers of objects in a box

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Abstract

Humans can acquire behaviorally relevant information about the contents of a container through their sense of touch. A container poses a challenge to the haptic sense as it creates an intermediary between its contents and the observer. Despite this challenge, several studies have shown that individuals are particularly adept at estimating small numbers of objects in an opaque box solely through tactile interaction. This study aimed to identify which physical cues contribute to this ability by systematically attenuating (Experiment 1) or augmenting (Experiment 2) the cues of rolling vibrations, impact, and weight. Rolling cues were manipulated by varying the friction between the objects and the container's floor. Impact cues were manipulated by softening or hardening the container's internal wall. Weight cues were controlled by equalizing the total weight of the contents, regardless of the number of objects. The findings suggest that rolling vibrations are the primary cues, followed by impact cues, while weight plays only a minor role.

Keywords Haptics · Numerosity · Container · Tactile cognition

Introduction

We, humans, are experts at gaining behaviorally relevant information from our environment through our sense of touch. To do so, we have a large repertoire of interactions with the environment that requires the integration of the tactile sense, the proprioceptive senses (muscular and vestibular systems), as well as the ability to control exploratory movement. This integrated whole is commonly referred to as the *haptic system* (Grunwald, 2008; Ziat, 2023).

Central to the study of the haptic system is the assumption that touch requires direct contact with an object of interest (e.g., Hatwell, 2003), such as when we enclose an object in our hands to feel its shape or rub it to feel its surface texture. However, this overlooks another kind of exploration: feeling objects that are prevented from being contacted directly inside a container. A container poses a challenge to

the haptic sense since it creates an intermediary between its contents and the observer. Yet, containers demonstrably provide sensory signals related to their content, which affords daily experiences such as shaking a juice can or rattling a box of chocolate sprinkles to estimate whether there is enough left to drink or to eat (Hirota & Sekiguchi, 2009; Plaisier & Smeets, 2017; Tanaka & Hirota, 2012).

As reviewed next, a small but consistent body of literature has established that people *can* reliably learn about various aspects of container content through their sense of touch. The present study considers *how* they do so by looking at haptic cues that are effective in estimating small numbers of objects in a container.

Literature review

Perceiving liquids and object motion

A handful of haptic container studies have investigated the perception of liquids and object motion. Two studies demonstrated that untrained participants were remarkably accurate in judging how many deciliters there are in a milk carton (Jansson et al., 2006) or milliliters in a bottle (Koshiyama et al., 2015). Two other studies have investigated whether

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people could spontaneously perceive the location of a real or virtual ball rolling inside a handheld tube (Frissen et al., 2022; Yao & Hayward, 2006). For instance, in the Frissen et al. (2022) study, participants wielded a fiberglass tube containing a physical ball and were asked to indicate the final resting location of the ball. Participants were surprisingly apt at performing this novel task, albeit with a tendency to underestimate distance as distances increased.

Perceiving numbers of objects

Most container studies have been concerned with numerosity judgments, that is, whether people can tell how many objects there are in the container. For instance, Frissen and Chen (2024) had participants estimate the number of objects in a container using two different tasks. Plastic food containers were filled to between ~15% and ~80% with large numbers of pieces of plastic straws (ranging between 34 and 648). The first task asked for an estimate of the absolute number of objects (e.g., “there are 200 objects in this container”), whereas the second task asked for a judgment in terms of proportion (e.g., “the container is 25% full”). While participants markedly underestimated the absolute number of objects, they retained the ability to accurately judge the numbers in terms of proportionality (i.e., doubling the amount of content led to a doubling in the estimate). It was perhaps not surprising then that performance on the second task, which required a proportional response, was highly accurate and that performance rates on the two tasks were significantly correlated. The correlation was interpreted as suggestive of common perceptual mechanisms.

More studies have looked at cases where there were much smaller numbers of objects (i.e., between one and eight) in the container (Frissen et al., 2022, 2023; Hummel et al., 2022; Overvliet et al., 2023; Plaisier & Smeets, 2017; Sekiguchi et al., 2005). The earliest one, by Sekiguchi et al. (2005), suggested that people can accurately discriminate up to three or four objects in a container. However, the study design did not allow any conclusions about whether participants accurately perceived the actual number of objects; they could only tell that there were different numbers.

Plaisier and Smeets (2017) directly demonstrated that people can estimate the exact number of spheres inside a small cardboard box, provided that number was between one and three. The task was performed under two conditions. In one condition, participants received auditory and haptic information from handling the box; in another, they heard playbacks of auditory recordings from that handling. Notably, the study did not include a haptic-only condition, limiting any conclusions about people’s ability to do the estimation task based on haptic cues alone. Two more recent studies replicated the Plaisier and Smeets study but included all three of these conditions using virtual (Hummel et al.,

2022) and real objects (Overvliet et al., 2023). Both studies suggested that the auditory cue was conducive to slightly more accurate performance than the haptic cue. They also both indicated that performance with having both cues available was on par with, and not better than, having only auditory cues.

Finally, the study by Frissen et al. (2023) is the only one to specifically look at number estimations based on haptic information only. In a series of three experiments in which any helpful visual and auditory cues were excluded, participants handled containers holding between one and five objects and verbally estimated their number. The containers were small cardboard jewelry boxes holding round beads of various diameters and weights. In Experiment 1, participants showed highly accurate performance as long as the objects had sufficient weight. Experiment 2 revealed that not disclosing the possible number of objects in the container did not affect group accuracy but did lead to occasional overestimations by some individual participants. In Experiment 3, removing the weight cue resulted in systematic underestimations, yet participants still managed to differentiate between different quantities of objects in the container.

Present study

As briefly reviewed above, several studies now demonstrate that people can extract reasonably accurate information about (small) numbers of objects using only their haptic senses. One question following this is what cues the haptic sense uses. Therefore, the present study aimed to replicate the study of Frissen et al. (2023) and determine the relative importance of three a priori tactile cues: *Weight*, *Impact*, and *Rolling* vibration.

The first potential cue is *Weight*. As a container is loaded with objects, its overall weight increases accordingly. The third experiment by Frissen et al. (2023) addressed the question of weight by eliminating it as a cue. This was accomplished by replacing the stimuli with three-dimensional (3D)-printed spheres constructed so that the total weight of the content remained constant. The results showed that removing the weight cue did not eliminate participants’ ability to do the task. However, it did seem that the number of objects was underestimated compared to using weighted objects. Since no direct comparison condition with weighted objects was included, the effect of the weight cue is currently under-determined.

The second cue is *Impact*. Each time an object hits a container wall, it produces an impulse-like signal proportional to its speed at the moment of impact. The third cue (*Rolling*) derives from the pattern of vibrations caused by an object rolling along the inner floor of a container.

The cue manipulation logic

The logic of the experimental manipulation is to try and target one or more cues and to alter them. The logic is akin to that used in Frissen et al., (2022; Experiment 2), which was designed to examine the types of tactile information potentially contributing to the estimation of the location of a rolling object inside a tube. The first cue, similar to the *Impact* cue described above, was the impact caused by the ball hitting the wall at either end of the tube. The second cue, similar to the *Rolling* cue, was the vibration caused by the ball rolling along the inner surface of a tube. A third cue was the elastic bounces of the ball upon impact. The experimental control of the various cue combinations was achieved using virtual haptics technology, as described by Yao and Hayward (2006). In brief, a tube handle featured an accelerometer and an actuator. The accelerometer returned a measurement directly proportional to a virtual ball's acceleration. The actuator was driven by a real-time computer simulation of the key aspects of the physics.

Using the virtual-reality (VR) setup, participants estimated the location of the object while being provided with various combinations of cues: impact only, rolling vibration only, impact plus rolling, impact plus bounce, and the combination of impact, rolling, and bounce. An additional reference condition had tubes with physical balls. The results suggested that the rolling vibration was the most potent information feeding into the estimation, the impact was the second most important, and the bounce's contribution was negligible.

While the VR setup afforded complete isolation and arbitrary combinations of impact and rolling cues, the same freedom is not given when working with physical containers as in the present study. The next best thing is to target one or more of the cues, attenuate or augment them, and track whether these manipulations change the perceptual estimate of the number of objects in the container. Accordingly, the contribution of the *Weight* cue is examined by directly comparing number estimates with weighted and weight-equalized stimuli. The contributions of the *Impact* and *Rolling* cues were examined by modifying the interior of the containers such that the cues were attenuated (Experiment 1) or augmented (Experiment 2).

Expected results

Concerning the *Weight* cue, based on Frissen et al. (2023), we expect estimates with weight-equalized objects to be smaller, if only marginally so, than estimates with weighted objects. As for the *Impact* and *Rolling* cues, the only comparison is the rolling object study by Frissen et al. (2022). While its task and stimuli differed from those in the current study, it is the only other study that manipulated *Impact* and *Rolling* cues in a container-like

scenario. We, therefore, based our naïve expectations on those results. Consequently, we expect the *Rolling* and *Impact* cues to be the first and second most important in estimating the number of objects in a container.

Experiment 1: Cue attenuation

Method

Participants

Twenty-four participants (11 females), ages 18–29 years (mean = 21.1, $SD = 3.7$), were recruited from Bentley University. Each received a \$15 gift card for participating in the experiment. All participants provided their informed consent. The study was approved by the Bentley University Institutional Review Board (IRB).

Materials

The containers were crafted from cardboard jewelry cases (with lids), with dimensions measuring 87 mm (L), 87 mm (W), and 28 mm (H).

Attenuation was implemented by covering the container floors with 2-mm thick velvet (Polyester) to reduce the rolling vibration and covering the walls with 3.18-mm thick high-density foam strips (used for weather stripping) to minimize the impacts. Table 1 breaks down the application of these materials to the containers.

A container could hold one, three, or five objects. The objects consisted of 3D-printed spheres with a uniform diameter of 22 mm. Two series of object types were created. For the first series ("Weighted objects"), the weight of each individual object was constant at 2.18 g. This meant that as more objects were placed in a container, the total weight of the objects increased. For the second series ("Weight-equalized objects"), the weight of the objects was manipulated such that no matter how many objects were in the container, their total weight remained constant (at 6.55 g). Thus, objects were created at 1.31, 2.18, and 6.55 g. Table 2 breaks down the various combinations of the number of objects and weights.

Design and procedure

The experiment used a 2 (Object Type: Weighted vs. Weight Equalized) $\times$ 4 (Containers) $\times$ 3 (Number of Objects: 1, 3, 5) $\times$ 6 (Repetition) within-subject design, with a total of 144 trials for each participant. Trial sequences were blocked by Repetition, and within each block, Object Type and Number of Objects were randomized.

Table 1 Content, treatment, and cues for the containers in Experiment 1

#	Object type	Treatment		Cues*			Shorthand*
		Walls	Floor	W	I	R	
1	Weighted Objects	No	No	o	o	o	W I R
2		No	Velvet	o	o	-	W I -R
3		Foam strips	No	o	-	o	W -I R
4		Foam strips	Velvet	o	-	-	W -I -R
5	Weight Equalized Objects	No	No	-	o	o	-W I R
6		No	Velvet	-	o	-	-W I -R
7		Foam strips	No	-	-	o	-W -I R
8		Foam strips	Velvet	-	-	-	-W -I -R

For the Treatment column: No=no alteration was done to the container walls or floor; Foam strips/Velvet indicates the type of treatment used to target cues. For Cues and Shorthand columns: R=Rolling vibration; I=Impact; W=Weight; o=the cue remained unaltered;—=the cue was attenuated (or removed in the case of the weight cue)

Table 2 Detailed measurements for objects used in the experiment

#Objects	Object type	Weight (g)		Dimensions (mm)	
		Per object	Total	Diameter	Thickness
1	Weighted objects	2.18	2.18	22	1.39
3		2.18	6.55	22	1.39
5		2.18	10.92	22	1.39
1	Weight-equalized objects	6.55	6.55	22	(Solid)
3		2.18	6.55	22	1.39
4		1.31	6.55	22	0.79

"Weighted objects" and "Weight-equalized objects" vary in weight and composition. The Weight columns show the weight per object and the cumulative total for each condition. The Dimensions columns list the Diameter and Thickness of each object

Prior to the experiment, participants were seated in front of a table facing the experimenter, instructed to clean their hands with hand wipes, and briefed on the experimental procedures. They were then asked to wear noise-cancelling headphones (Bose QuietComfort 45) that played pink noise throughout the test. The volume of the background noise was adjusted to minimize auditory cues without causing discomfort. Participants were also asked to wear a blindfold to eliminate potential visual clues from the experimenter or the containers.

In each trial, the experimenter placed a container on the participant's hand, allowing them approximately 5–10 s to manipulate the container and estimate the number of objects inside. Participants were encouraged to explore the container without flipping it over to avoid objects falling out and to ensure that the perceptual cues came from the floor, not the untreated lid. After the participants determined the number, they vocalized their answers, which the experimenter recorded in a spreadsheet. The experimenter also took notes to document observations.

To mitigate the fatigue of repetitive tasks with continuous background noise, participants were asked to remove the

blindfold and the headphones for a short break after every two blocks. No familiarization with the stimuli, practice trials, or feedback about accuracy were provided. Upon completing all trials, participants were asked about any perceived differences between containers beyond the object count. The experimenter then revealed the actual contents and recorded the participants' reactions.

Data analysis

Matlab (The MathWorks Inc., 2022) was used for data processing and visualization. In descriptive statistics and figures, all intervals and error bars represent 95% empirical bootstrapped ($n = 10,000$) confidence intervals. Inferential statistical analyses, assuming a level of significance of 5%, were performed in JASP (JASP Team, 2023). We follow Bakeman's (2005) recommendation for effect sizes and report Generalized Eta-squared values (η_G^2). As no comparable data exist in the literature, we default to the guide by Cohen (1988) for interpreting effect sizes: < 0.01 = trivial; 0.01 = small; 0.06 = medium; 0.14 = large.

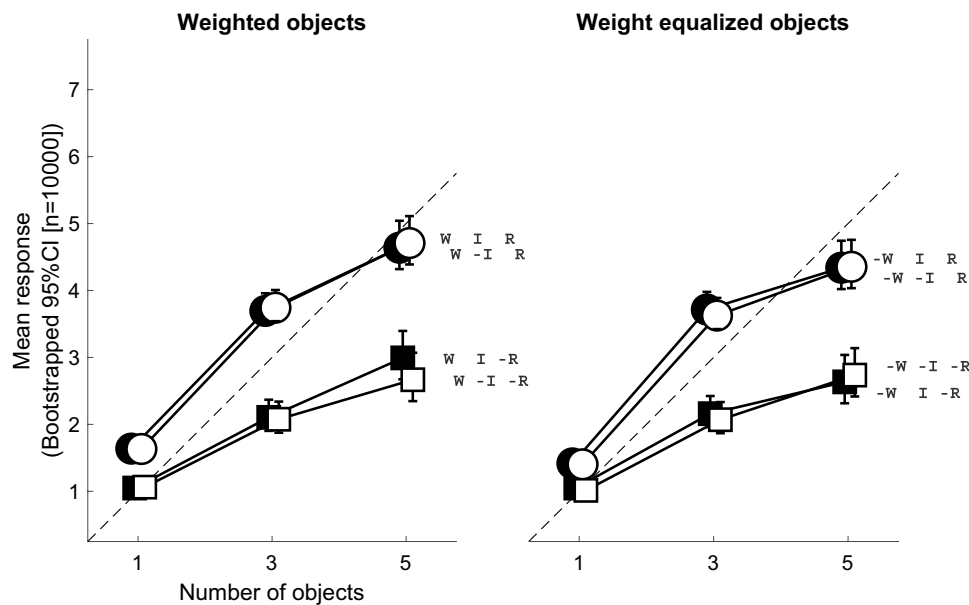


Fig. 1 Main results for Experiment 1. Error bars represent 95% empirical bootstrapped ($n=10,000$) confidence intervals. The series labels correspond to the coded conditions as listed in Table 1

Results and discussion

Figure 1 plots the group average estimates, allowing for several observations. First, there appears to be only a minor difference in performance with the weighted (left panel) and weight-equalized objects (right panel). Second, attenuating the Impact cue had no noticeable effect. Third, attenuating the Rolling cue had an unmistakably large effect on the estimates. These observations, and the effect of the Rolling cue in particular, held even at the level of individual participants (see Appendix A).

The visual appreciation of the results was supported by a 2 (*Weight*: Weighted objects vs. Weight-equalized objects) $\times$ 2 (*Impact*: Unattenuated vs. Attenuated) $\times$ 2 (*Rolling*: Unattenuated vs. Attenuated) $\times$ 3 (*nrObjects*: 1, 3, 5) repeated-measures ANOVA (see Table 3 for details).

Main effects. The main effects of *Weight*, *Rolling*, and *nrObjects* were all significant. However, whereas the effect sizes for *Rolling* and *nrObjects* were large (both $\eta^2_G > 0.45$), that for *Weight* could be considered to be trivial ($\eta^2_G < 0.01$).

Interactions. Three interactions were significant, although only one, *Rolling* $\times$ *nrObjects*, had a non-trivial effect size ($\eta^2_G = 0.14$). This interaction could be attributed to the fact that the effect of the *Rolling* factor increased with the number of objects.

Two findings were consistent with our expectations. First, the *Weight* cue did not figure in any significant way in estimating the number of objects in the container. Second, the *Rolling* cue was clearly the dominant cue; indeed, it was the only cue that produced a significant and large effect size.

Contrary to our expectations, the *Impact* cue had no discernible effect, suggesting that it was inconsequential to estimating the number of objects in the container. However, before accepting this conclusion, we must entertain the possibility that the *Impact* cue manipulation (i.e., the foam wall strips) was ineffective. This is addressed in Experiment 2.

Experiment 2: Cue augmentation

The second experiment followed the same procedure as Experiment 1. The only difference was in the treatment of the containers. The objective now was to augment the target cues. In addition, we attenuated the non-target cue to increase the “contrast” of a target cue, as in Experiment 1.

Method

Participants

Twenty-four new participants (15 females) were recruited from the same pool, with ages ranging between 18 and 35 years (mean = 21.5, $SD = 4.3$). Each received a \$15 gift card for participating in the experiment.

Materials

Augmentation was implemented using sandpaper on the floors to exaggerate the rolling vibration and plastic strips

Table 3 Details for the repeated-measures ANOVA for Experiment 1

Effect		df	F	MS	p	η^2G
Main	Weight	1, 23	17.05	2.22	< 0.001	0.0080
	Impact	1, 23	0.80	0.12	0.381	0.0004
	Rolling	1, 23	217.72	233.92	< 0.001	0.4530
	nrObjects	2, 46	204.48	277.75	< 0.001	0.6630
First order	Weight x Impact	1, 23	0.15	0.01	0.698	0.0000
	Weight x Rolling	1, 23	5.58	0.83	0.027	0.0030
	Impact x Rolling	1, 23	1.35	0.15	0.258	0.0005
	Weight x nrObjects	2, 46	6.26	0.60	0.004	0.0040
	Impact x nrObjects	2, 46	0.15	0.01	0.863	0.0001
	Rolling x nrObjects	2, 46	82.88	23.10	< 0.001	0.1410
Second order	Weight x Impact x Rolling	1, 23	2.45	0.27	0.131	0.0010
	Weight x Impact x nrObjects	2, 46	2.71	0.27	0.077	0.0020
	Weight x Rolling x nrObjects	2, 46	0.81	0.06	0.453	0.0004
	Impact x Rolling x nrObjects	2, 46	1.38	0.08	0.262	0.0005
Third order	Weight x Impact x Rolling x nrObjects	2, 46	2.29	0.23	0.113	0.0020

Table 4 Content, treatment, and cues for the containers in Experiment 2

#	Objects	Treatment		Cues*			Shorthand*
		Walls	Floor	W	I	R	
1	Weighted objects	No	No	o	o	o	W I R
2		Plastic strips	Velvet	o	+	-	W + I - R
3		Foam strips	Sandpaper	o	-	+	W - I + R
4		Plastic strips	Sandpaper	o	+	+	W + I + R
5	Weight-equalized objects	No	No	-	o	o	- W I R
6		Plastic strips	Velvet	-	+	-	- W + I - R
7		Foam strips	Sandpaper	-	-	+	- W - I + R
8		Plastic strips	Sandpaper	-	+	+	- W + I + R

For the Treatment column: No=no alteration was done to the container walls or floor; Foam strips/Velvet indicates the type of treatment used to target cues. For Cues and Shorthand columns: R=Rolling vibration; I=Impact; W=Weight; o=the cue remained unaltered;—=the cue was attenuated (or removed in the case of the weight cue); +=the cue was augmented

on the wall to exaggerate the impacts. The sandpaper was 2 mm thick and 40 grit, glued to the container's floor. The plastic strips were 0.51 mm thick and made from durable PVC. Table 4 breaks down the application of the various materials to the containers. Note that the same velvet and foam strips from Experiment 1 were used to increase the contrast of the particular augmented cue.

Results and discussion

Figure 2 plots the group average estimates, allowing for several observations. First, there appears to be only a minor difference in performance with the weighted (left panel) and weight-equalized objects (right panel). However, some tendencies toward smaller estimates can be seen for the weight-equalized object conditions compared to their weight-object

counterparts. Second, the *Rolling* cue again had an unmistakable effect on the estimates. As in Experiment 1, attenuating the *Rolling* cue (black squares) produced underestimations, while augmenting the *Rolling* cue produced estimates larger than the baseline condition (gray circles and gray squares). These observations held whether the objects were weight equalized or not. Third, contrary to Experiment 1, the *Impact* cue did appear to have an effect. Specifically, in the conditions where both the *Impact* and the *Rolling* cue were augmented, we saw the largest estimates (gray squares). These estimates were larger than when the *Impact* cue was attenuated and the *Rolling* cue was augmented (gray circles), suggesting an interaction between the two cues. These observations roughly held true at the level of individual participants (see Appendix B).

The visual appreciation of the results was supported by a 2 (*Weight*: Weighted objects vs. Weight-equalized objects) × 2

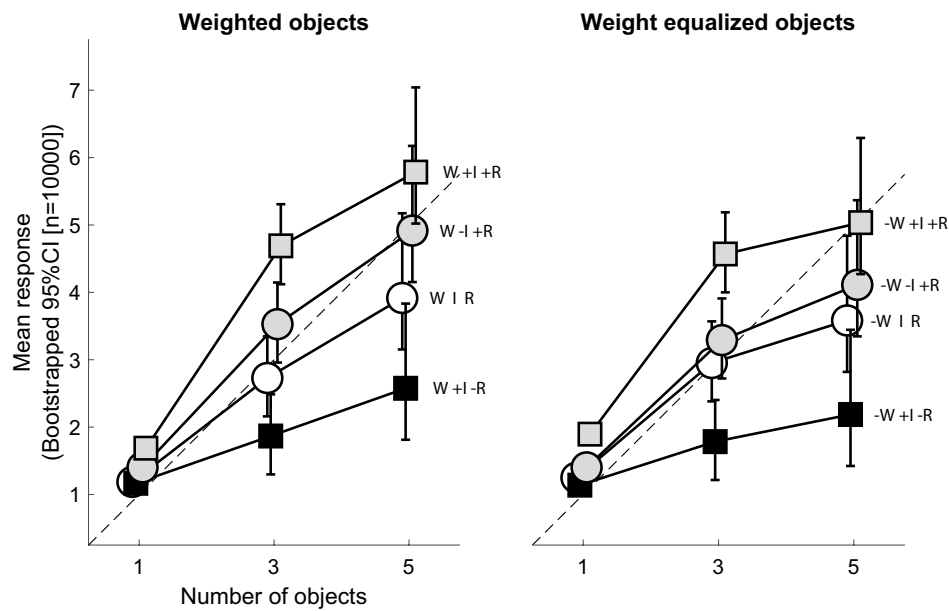


Fig. 2 Main results for Experiment 2. The series labels correspond to the coded conditions as listed in Table 4

Table 5 Details for the repeated-measures ANOVA for Experiment 2

Effect		df	F	MS	p	η^2_G
Main	Weight	1, 23	14.40	5.08	<0.001	0.0060
	Impact	1, 23	0.01	0.01	0.909	0.0000
	Rolling	1, 23	56.18	255.20	<0.001	0.2430
	nrObjects	2, 46	94.98	344.47	<0.001	0.4640
First order	Weight x Impact	1, 23	0.02	0.01	0.900	0.0000
	Weight x Rolling	1, 23	6.54	1.34	0.018	0.0020
	Impact x Rolling	1, 23	49.24	98.12	<0.001	0.1100
	Weight x nrObjects	2, 46	12.96	5.41	<0.001	0.0130
	Impact x nrObjects	2, 46	7.06	2.21	0.002	0.0060
	Rolling x nrObjects	2, 46	23.24	30.98	<0.001	0.0720
Second order	Weight x Impact x Rolling	1, 23	2.07	0.69	0.164	0.0009
	Weight x Impact x nrObjects	2, 46	0.33	0.07	0.719	0.0002
	Weight x Rolling x nrObjects	2, 46	4.34	0.79	0.019	0.0020
	Impact x Rolling x nrObjects	2, 46	17.66	12.88	<0.001	0.0310
Third order	Weight x Impact x Rolling x nrObjects	2, 46	0.33	0.07	0.724	0.0002

(*Impact*: Unaltered/Attenuated¹ vs. Augmented) $\times$ 2 (*Rolling*: Unaltered/Attenuated vs. Augmented) $\times$ 3 (*nrObjects*: 1, 3, 5) repeated-measures ANOVA (see Table 5 for details).

Main effects. Similar to Experiment 1, the main effects of *Weight*, *Rolling*, and *nrObjects* were all significant. However, while the effect sizes for *Rolling* and *nrObjects* were

large (both $\eta^2_G > 0.24$), that for *Weight* could be considered to be trivial ($\eta^2_G < 0.01$).

Interactions. Six interactions were significant, of which two had effect sizes that were considered trivial (*Impact* $\times$ *nrObjects* and *Weight* $\times$ *Rolling* $\times$ *nrObjects*). Of the remaining four interactions, the one with the largest effect size was *Impact* $\times$ *Rolling* ($\eta^2_G = 0.11$), which could be attributed to the fact that the overall effect of the *Rolling* cue was stronger when the *Impact* cue was also present. In other words, the two cues seemed to reinforce each other. The second largest effect size was for *Rolling* $\times$ *nrObjects* ($\eta^2_G = 0.07$;

¹ The nuance “unaltered/attenuated” is to indicate that except for the baseline condition with no manipulation of the container, the non-target cue was attenuated in order to increase the contrast with the target cue (see also text).

“medium”). This is the same interaction seen in Experiment 1 and reflects the fact that the effect of the *Rolling* factor increased with the number of objects. The third largest effect size was for *Impact* $\times$ *Rolling* $\times$ *nrObjects* ($\eta^2_G=0.03$; “small to medium”), reflecting the combination of the two interactions just described. That is, the increasing effect of the *Rolling* cue as a function of *nrObjects* is larger when the *Impact* cue is present than when it is not. Taken together, these three statistical interactions show that the *Impact* cue has a role to play, but it is dependent on the presence of the *Rolling* cue. This result is similar to that of Frissen et al. (2022).

Finally, the smallest significant effect size was for *Weight* $\times$ *nrObjects* ($\eta^2_G=0.01$; “small”). This interaction can be attributed to the fact that there was an effect of *Weight* but only for the conditions with five objects in the container. Specifically, with five objects, the estimates with the *Weight*-equalized objects were slightly smaller than for the *Weighted* objects; the differences were 0.06 [−0.03; 0.15], −0.05 [−0.24; 0.08], and −0.57 [−0.85; −0.36], for one, three, and five objects, respectively.

With the new stimulus configurations, the findings were consistent with all three of our expectations. First, except for a minor “local” effect, the *Weight* cue again did not significantly affect the estimation of the number of objects in the container. Second, the *Rolling* cue was again the dominant cue. Third, the *Impact* cue now did have a measurable effect, albeit only in conjunction with the *Rolling* cue.

General discussion

The present study had two objectives. The first was to replicate the main finding of Frissen et al. (2023). The baseline conditions in both experiments again demonstrated people’s ability to accurately estimate small numbers of objects from touch alone. This means that this particular haptic ability has now been documented in eight separate experiments that included haptic-only conditions across four published studies (Frissen et al., 2023; Hummel et al., 2022; Overvliet et al., 2023), making it a replicable and robust finding.

The second and primary objective was to determine the relative importance of three a priori tactile cues: *Weight*, *Impact*, and *Rolling* vibration. The suggestion put forward by Frissen et al. (2023) that *Weight* was not an essential cue in the number-estimation task has now been confirmed twice in the current study. While the statistical results for both experiments showed significant main effects of, and interactions involving, the *Weight* factor, all of these were associated with trivial effect sizes. The only exception was related to a slight decrease in the number estimation when there were five objects in the container.

The most directly apparent finding of this study was that the *Rolling* cue was the most consequential of the three cues under

consideration here. This was most obvious in the first Experiment, where a simple visual inspection of the group results showed an unmistakable difference between conditions without and with the attenuated *Rolling* cue. This difference held at the level of individual results, showing the robustness of the effect. The robustness of the effect of attenuating the *Rolling* cue was further demonstrated by its replication in the second Experiment.

The results for the *Impact* cue were less straightforward than those for the *Weight* and *Rolling* cues. Whereas the cue appeared inconsequential in the first experiment, it did manifest a role in the second experiment. Our current explanation for this apparent discrepancy is that our attenuation manipulation in the first Experiment was suboptimal at best or plain ineffective at worst. Nevertheless, the second Experiment does demonstrate a role for the cue. Taken at face value, the relation between the *Rolling* and *Impact* cues bears a resemblance to that found by Frissen et al.’s (2022) study of the relative importance of haptic cues in estimating the location of a ball rolling in a tube. While that scenario and task were markedly different from the current number-estimation task, it also showed that the *Rolling* cue took precedence over the *Impact* cue and that the latter depended on the former.

This study is the first to try to tease apart the various potential haptic cues used in determining small numbers of objects in a container and is, therefore, bound to have limitations. For instance, the relative importance of the *Impact* cue might still be under-determined. If the attenuation were truly ineffective, then this would qualify the findings of Experiment 2 since the stated objective of increasing the contrast of the target cue would have been differentially effective for the conditions in which we were attenuating the *Impact* cue (i.e., in the conditions that targeted the *Rolling* cue for augmentation). More generally, the current cue manipulation approach only provides a quasi-quantification of the relative importance of the three cues. In other words, it only allows us to rank the cues: *Rolling*, then *Impact*, then *Weight*. However, we cannot put numeric perceptual weights on any of them. Such a determination would require complete control over the isolated cues, control that is impossible with the current physical stimulus set and that can only be gained by employing VR technology. This technology is currently not readily available.

Another area for improvement is that it remains an open question to what extent the findings will generalize. We need to determine whether the ranking of cues observed with our current stimulus set would hold for other stimulus sets. For instance, imagine spheres made of a material with a low friction coefficient with the floor (and therefore a reduced *Rolling* cue), but that is hard enough to produce salient hits against the container walls. It seems reasonable to assume that such a configuration would change the relative importance of the *Impact* and *Rolling* cues. Likewise, the *Weight* cue might become effective with heavier objects. Such variations need to be explored in future work.

Conclusion

The study of container haptics asks how good haptic perception is at learning about things hidden from direct touch inside a container. While container haptics research is still in its early days, there are now clear indications that a container can be haptically “transparent” enough

to convey behaviorally relevant information to a person handling it. Currently, the most investigated of such transparencies is that which allows for determining small numbers of objects in containers. The present study not only reconfirmed this ability but has also made a start at determining the psychophysical dimensions on which that ability is based.

Appendix

See Figs. 3 and 4

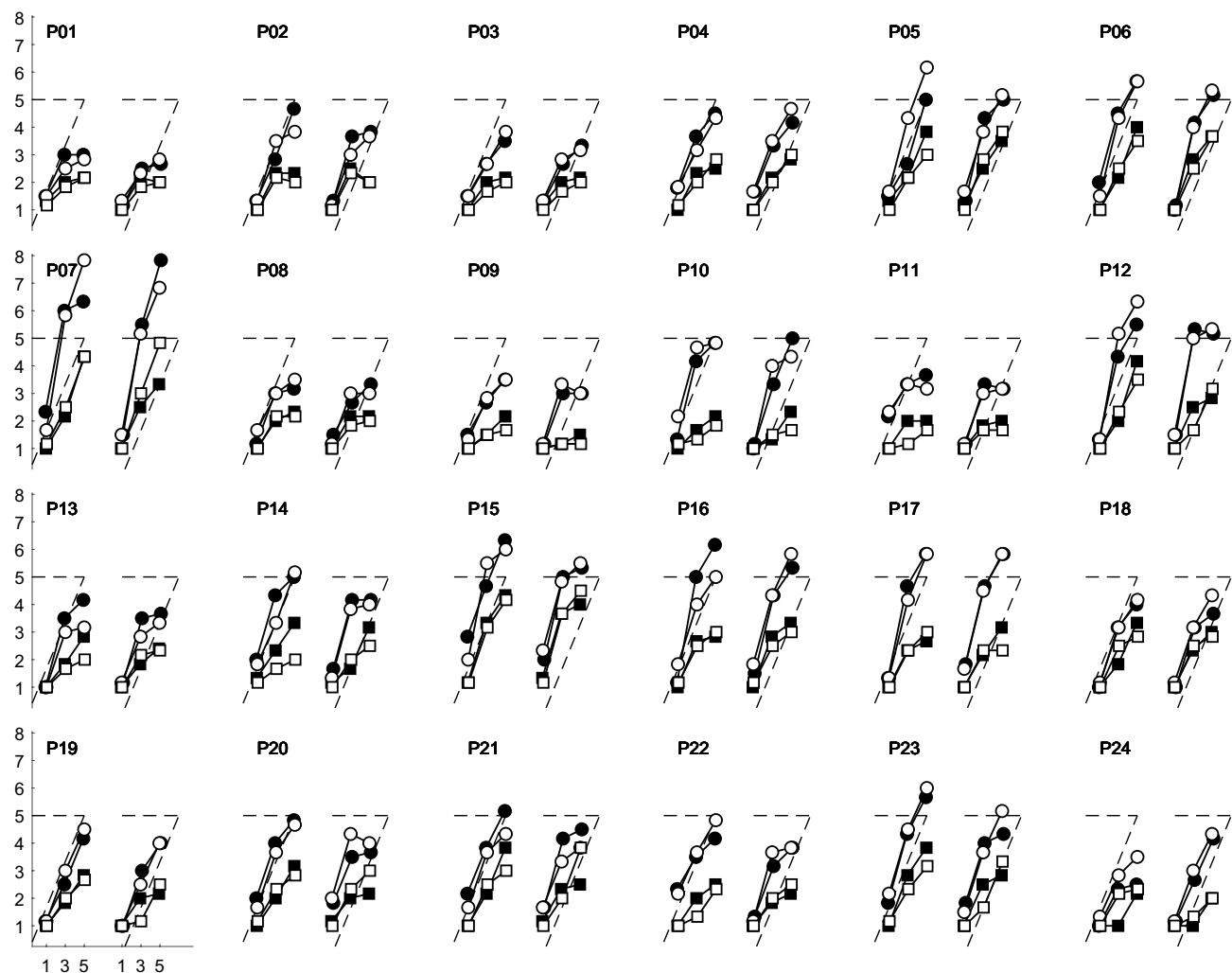


Fig. 3 Individual results for Experiment 1. See Fig. 1 for the legend

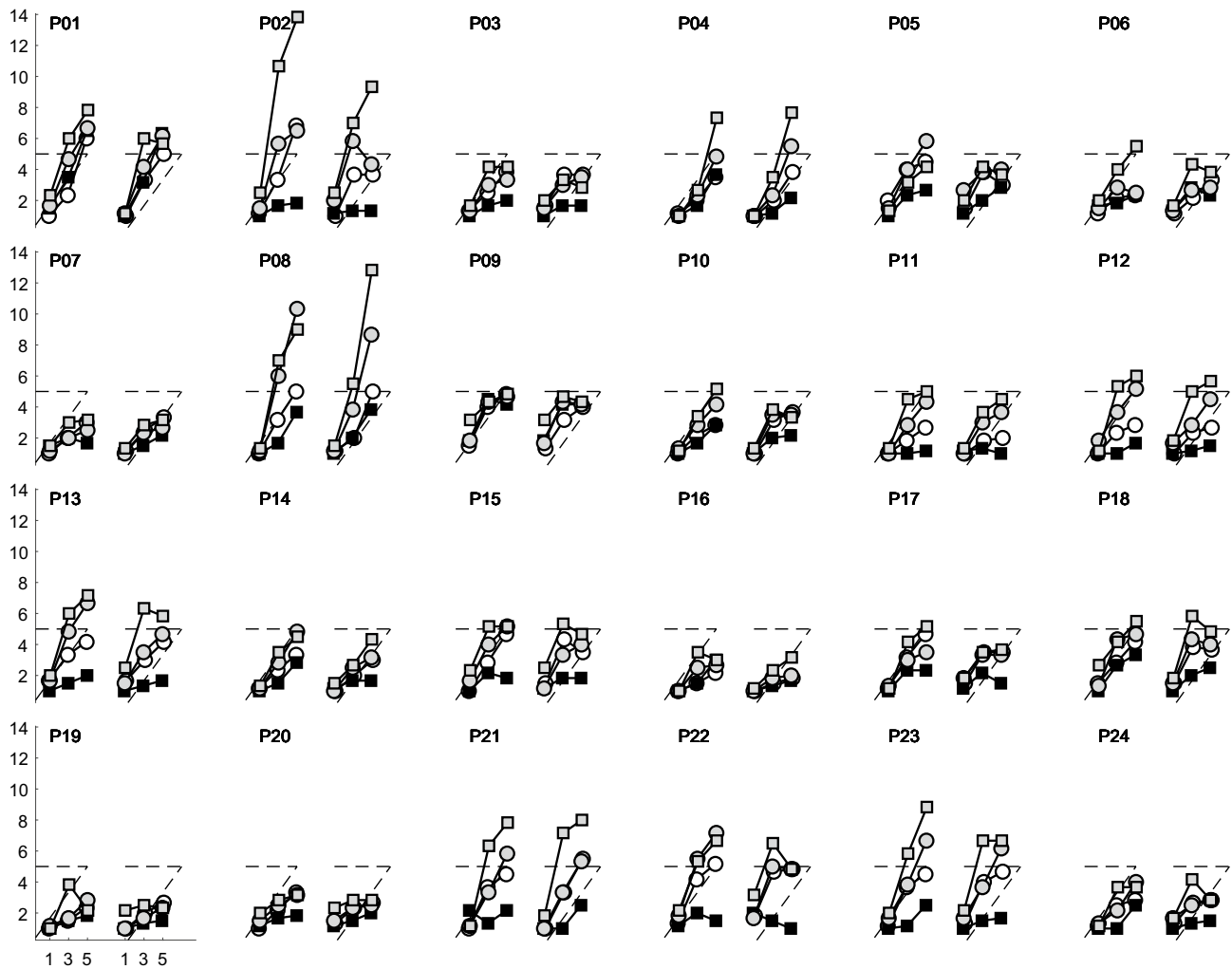


Fig. 4 Individual results for Experiment 2. See Fig. 2 for the legend

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Data availability The datasets and STL files for the 3D printed stimuli used for the current study are available upon reasonable request. These experiments were not preregistered.

Code availability Not applicable.

Declarations

Ethics approval The study was approved by the Bentley University Institutional Review Board (IRB).

Consent to participate All participants provided their informed consent.

Consent for publication All participants provided their informed consent.

Conflicts of interest/Competing interests The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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