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Investigating Students' Ideas About Buoyancy and the Influence of Haptic Feedback

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Abstract While haptics (simulated touch) represents a potential breakthrough technology for science teaching and learning, there is relatively little research into its differential impact in the context of teaching and learning. This paper describes the testing of a haptically enhanced simulation (HES) for learning about buoyancy. Despite a lifetime of everyday experiences, a scientifically sound explanation of buoyancy remains difficult to construct for many. It requires the integration of domain-specific knowledge regarding density, fluid, force, gravity, mass, weight, and buoyancy. Prior studies suggest that novices often focus on only one dimension of the sinking and floating phenomenon. Our HES was designed to promote the integration of the subconcepts of density and buoyant forces and stresses the relationship between the object itself and the surrounding fluid. The study employed a randomized pretest–posttest control group research design and a suite of measures including an open-ended prompt and objective content questions to provide insights into the influence of haptic feedback on undergraduate students' thinking about buoyancy. A convenience sample ($n = 40$) was drawn from a university's population of undergraduate elementary education majors. Two groups were formed from haptic feedback ($n = 22$) and no haptic feedback ($n = 18$). Through content analysis, discernible differences were seen in the posttest explanations sinking and floating across treatment groups. Learners that experienced the haptic feedback made more frequent use of "haptically grounded" terms (e.g., mass, gravity, buoyant force, pushing), leading us to begin to build a local theory of language-mediated haptic cognition.

Keywords Science learning · Buoyancy · Haptic technology · Grounded cognition

Introduction

This article describes the testing of a haptically enhanced simulation (HES) for learning about buoyancy. The term "haptic" comes from the Greek *haptikos* which means "able to touch" (Revesz 1950; Katz 1989). Our (HES) incorporated force feedback (simulating objects' weight due to gravitational force and buoyant forces) in addition to the visual information presented. Force feedback haptic devices engage physical receptors in the hand and arm to gather sensory information as users "feel" and manipulate two- and three-dimensional virtual objects and events (Jacobson et al. 2002). More details regarding our user interface and simulation are provided in "Materials and Methods" section.

Despite the acceleration of haptic technology and a growing research base that looks specifically at haptics within the context of teaching and learning (e.g., Bivall Persson et al. 2011; Han and Black 2011; Jones et al. 2006; Minogue et al. 2006b; Reiner 1999; Schönborn et al. 2011; Wiebe et al. 2009; Williams et al. 2003), the "science simulation literature" remains dominated by work studying simulations that offer only visual and audio feedback (e.g., de Jong 2006; Mayer 2005; Mayer and Moreno 2003;

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Smetana and Bell 2006). Our research helps fill the gap here, but this gap remains quite wide.

The power of actively involving learners via "hands-on" activities has been espoused throughout history, and long-held theoretical claims about the cognitive impact of active touch exist (e.g., Dewey 1902; McMurray 1921; Piaget 1954; Fitts and Posner 1967; Wadsworth 1989; Reiner 1999). It has even been suggested that the addition of haptic feedback evokes experiential or embodied knowledge that would otherwise lie untapped (e.g., Barsalou 2008; Gibbs 2005; Glenberg 1997), but core questions about the potency of simulated touch in education remain unanswered. The study detailed here sheds some much-needed light on the notion that incorporating haptic force feedback can influence and possibly facilitate learning about complex core science ideas. The core research question in this exploratory study was: *How does haptic feedback influence users' understandings of buoyancy*.

Study Framework

Our study relates to prior work in two main areas: research into students' understandings of and reasonings about buoyancy (sinking/floating) and the emerging body of research on embodied cognition (particularly as it relates to science education and haptics). Each area is described in turn below.

Students' Thinking About Sinking and Floating

Buoyancy is a common and directly observable science phenomenon. We see ships and ice cubes floating all the time. Toddlers informally experiment with sinking and floating objects when given access to the materials (e.g., bath time and in the pool). But despite a lifetime full of everyday experiences, a scientifically sound explanation of buoyancy is difficult to construct. It turns out that the science behind sinking and floating is complex, and often largely inaccessible in traditional instructional settings. The "big idea" or core concept of interest is *Archimedes' Principle* which states that any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object. This principle explains why an object sinks or floats, but to be fully grasped and operationalized it requires domain-specific knowledge regarding (at a minimum) the concepts of: density, fluid, force, gravity, mass, weight, and buoyancy.

There exists a relatively long history of research looking into how students (pre-K to undergraduate) think about sinking and floating; some of the key work in this area is described below. Kohn (1993) developed and used a buoyancy prediction task as a way to access preschoolers' (3- to 5-year-old children) and adults' understandings of density by having them make buoyancy predictions for a set of objects that varied systematically in density, weight, and volume. Interestingly, 4- to 5-year-olds and adults showed similar patterns in their judgments; weight and volume were often conflated in their judgments, and objects much more or much less dense than water were more accurately judged than objects with densities closer to the density of water. In an earlier study, Halford et al. (1986) pointed to a size–weight illusion (that smaller objects appear denser and seem to weigh more per unit volume) to explain the difficulties that children aged 7–13 had when asked to judge which one out of three wooden blocks would float (or sink), given weight and volume information for each block relative to a block that was known to float (or sink). Using a repeated-measures design (pretest, posttest, 1-year follow-up) with 161 third graders, Hardy et al. (2006) investigated this science domain by comparing two curricula that differed in sequencing of content and amount of cognitively structuring statements used by teachers. Not surprisingly, they reported that instructed groups showed significant gains relative to a baseline group without instruction, and one year later, those that received high instructional support retained more accurate understandings when compared to the low instructional support group.

Loverude et al. (2003) investigated undergraduate science majors' understandings of hydrostatics using a series of "five-block problems" and subsequent cognitive interviews. Their work suggested that instruction on hydrostatics does not help learners predict and explain the sinking and floating behavior of simple objects (blocks). Specifically, many students were unable to identify the forces exerted on an object by a fluid and often failed to recognize the factors that govern the magnitudes of those forces, despite having learned the buoyancy formula. Many subjects also failed to consider the role of the displaced volume of liquid when trying to determine the buoyant force. They found that many learners held the common misconception that sinking and floating depend on mass alone and that many failed to differentiate the role of mass and volume in determining buoyancy. A lack of appreciation of Newtonian dynamics, despite the successful completion of an introductory physics course, was cited as a key reason for the observed difficulties. In their sample, many relied on their intuition to explain the sinking/floating phenomena rather than a clear line of reasoning that led to their predictions. Similar conceptual difficulties were found in research conducted by Parker and Heywood (2000) exploring pre-service and in-service teachers' learning about forces within the context of floating and sinking. This work involved a series of hand-on activities including pushing an inflated balloon into a tank of water, exploring of a range of everyday objects with respect to floating and sinking, and a floating screw cap jar in a tank of water.

Libarkin et al. (2003) suggested that common density misconceptions resulted from over-generalizations of size, shape, and material to explain their observations. More precisely, they found that students with size misconceptions believed that all large objects sink in water and small objects float. Students that over-generalized around an object's shape tended to view it as the determining factor. Yin (2005) used an experiment involving 1002 sixth and seventh graders to determine 10 commonly held misconceptions about sinking and floating. These include: big/heavy things sink and small/light things float; hollow things float and things with air in them float; things with holes sink; flat things float; the sharp edge of an object makes it sink; vertical things sink and horizontal things float; hard things sink and soft things float; floating fillers (e.g., life preservers) help heavy things float; a large amount of water makes things float; and sticky liquid makes things float. Based on this work, Yin et al. (2008) designed 10 two-tiered multiple-choice items to help teachers diagnose prevalent misunderstandings related to why things sink or float.

Taken together, prior studies of people's thinking about buoyancy suggest that individuals (of all ages) often focus on only one dimension of the sinking and floating phenomenon, hampering their ability to appreciate the underlying reason for the observed sinking/floating phenomenon (e.g., Ginns and Watters 1995; Halford et al. 1986; Hardy et al. 2006; Kohn 1993). Understanding and explaining the sinking and floating phenomena also asks learners to consider opposing forces; some earlier work describes the common conceptual difficulties that lie here (e.g., Driver et al. 1994; Heywood and Parker 2001). Our simulation (described further below) promotes the integration of the subconcepts of *density* and *buoyant forces* and stresses the relationship between the object itself and the surrounding fluid seeking to overcome previously documented conceptual pitfalls.

At first blush, there is strong theoretical logic behind the positive benefits of haptic technology in education, yet the existing research literature does not provide a clear answer to its efficacy. As we have suggested elsewhere (Minogue and Jones 2006a), this is due in large part to the fact that much of our current understanding of haptic information processing (as it relates to teaching and learning) is bounded by the fact that much of the foundational research regarding haptic perception and cognitive processing has been conducted with subjects in controlled settings deprived of vision (e.g., Klatzky and Lederman 2002; Klatzky et al. 1993; Lederman and Klatzky 1987, 1990; Lederman et al. 1996). Our simulation is different in that some users had access to both visual and haptic feedback.

When users have access to both visual and haptic information as they progress through an instructional program, the findings get murky. While the affective impact (e.g., interest, excitement, engagement) has been documented fairly consistently (e.g., Jones et al. 2006; Minogue et al. 2006; Reiner 1999; Williams et al. 2003), it has been difficult for the research community to tease out the differential impacts of haptics (assuming they exist). Embodied cognition, a relatively new approach to examining human cognition, may provide some insights.

Embodied Cognition and Haptics

Generally speaking, the embodied cognition approach emphasizes the importance of action and perception in conceptual learning. More traditional theories of cognition suggest that knowledge is a network of abstract propositions or images stored in long-term memory in a format of semantic memory systems that are separated from our bodily action and perception. However, a growing number of researchers (e.g., Barsalou 2008; Barsalou et al. 2003; Gibbs 2005; Glenberg 1997; Lakoff and Johnson 1999) have asserted that thought and knowledge emerge from dynamic interactions between the body and the physical world. This notion is what makes haptic devices so attractive; they have the unparalleled ability to provide tactile and kinesthetic feedback to users by employing physical receptors in the body (Minogue and Jones 2006). This theoretical lens is gaining some traction in science education as evidenced by the recent special issue: Conceptual Metaphor and Embodied Cognition in Science Learning (Amin et al. 2015).

In our work, we adopt the term "grounded cognition" coined by Barsalou (2008) because it underscores the idea that cognition is not only determined from physical states, but also can actually be drawn from multiple sources, including perceptual simulations and situated action (Han and Black 2011). This framework suggests that multimodal mental representations created by physical interactions serve as a cognitive grounding for understanding abstract (science) concepts, and we suggest that simulated haptic force feedback can facilitate this process.

Teaching Science Concepts with Simulated Touch

Our previous work includes a fairly comprehensive critical review of the research into "haptics in education" that existed up to 2004 or so (Minogue and Jones 2006). As mentioned earlier in this paper, since then there have been several studies that have investigated the use of haptic technology to teach about science concepts. Key findings from this newer research that informed our study are highlighted below.

Jones et al. (2014) explored the efficacy of a haptic simulation built to teach adolescent students ($n = 15$) with visual impairments about heat and pressure concepts. Their simulation, *Pollen Grain*, enabled users to control a virtual pollen grain that was constantly subjected to the random motion of surrounding particles in a closed system. Participants were able to "feel" the numerous particles randomly bombard the pollen grain and the magnitude of the force feedback varied according to the temperature and pressure set by the user. They point to statistically significant pre-to-post differences on their multiple-choice knowledge assessment and suggest that the haptic force feedback made the abstract concepts easier to understand.

Schönborn et al. (2011) explored university-level users' ($n = 20$) interactions with a haptic virtual model representing the specific binding of ligand and protein molecules during a docking task (finding the most favorable position). Students' interactions with the model were logged, and using multivariate parallel coordinate analyses, they found that the *haptics* group produced a tighter constellation of collected final docked ligand positions in comparison with *no-haptics* students. They found that haptic users had greater learning gains and engaged in fewer visual representational switches. Unlike much of the earlier research suggesting that haptic feedback increases working memory demands (Connell and Lynott 2009), they suggest that visual and haptic coordination may offload the visual pathway by placing less strain on visual working memory. They go on to postulate that, from their embodied cognition lens, sensorimotor (haptic force feedback) interactions (in the macroworld) can aid in the construction of knowledge about submicroscopic phenomena. These findings help reinforce the motivation for our study.

Our exploratory work presented here also builds on the study by Han and Black (2011) that examined the effectiveness of haptics on elementary students' creation of a multimodal representation of how gears work. They tested three conditions with fifth-grade students ($n = 175$) using a Microsoft Sidewinder Force Feedback Joystick. Their non-haptic simulation (NH) had only visual feedback (how fast each gear rotates, how much input force was needed, and output forces generated) and auditory information. The kinesthetic simulation (K) delivered the same scientific content, but there was no force feedback just the kinesthetic movement of the users' joystick and visual and auditory information. The force and kinesthetic (FK) condition received information through visual, auditory, and haptic force feedback (an actual feeling of the input force that they should use to rotate the gears). Their results on a recall test of factual knowledge about the gears' movements showed that the haptic-augmented simulations (both the FK and K conditions) were more effective than the equivalent non-haptic simulation in providing perceptual experiences and helping elementary students create multimodal representations of the movements of gears. They go on to suggest that bodily (haptic) perceptual experiences serve as cognitive grounding for the fuller understanding of physics and its underlying (often invisible) forces. In the current study, we too try to hone in on embodied cognition as a way to isolate and describe the influences of haptic feedback.

Materials and Method

Our Interface

Point-probe devices like the one used in our study track the *x*-, *y*-, and *z*-coordinates of the virtual point probe that the user moves about a 3D workspace. Actuators (motors within the device) communicate calculated forces back to the user's fingertips and arm. Haptic devices are often used to simulated the sense of touch based on collision detection with virtual objects, but can also be used to present other calculated forces. The haptic device of choice in this study is the Falcon® (Fig. 1) from Novint Technologies, Inc. (http://www.novint.com/). All haptic interface devices share the unique ability to provide for the bidirectional exchange of information between a user and a machine, an important distinction from other more passive interfaces (Minogue and Jones 2006).

Although still on the fringe of classroom learning technologies, haptics (simulated touch) has the potential to radically change the way in which learners interact with science concepts. Haptics may help fill gaps in an individual's chain of reasoning about abstract ideas by providing concrete (albeit simulated) experiences with invisible forces. These conceptual encounters with the invisible are often difficult or impossible to create in real-world scenarios.

Fig. 1 The Novint Falcon®

Our Haptically Enhanced Simulation

Our haptically enhanced simulation (HES) for learning provided control sliders to adjust the densities of the object and the surrounding liquid and the size of the object being "held." Users could see force arrows in the fluid and on the objects. These arrows were visualizations of the gravitational (red arrow) and buoyant force (aqua arrows) associated with the sinking and floating of objects. The buoyant force arrow is connected to a slightly darker layer of liquid representing the amount of displaced liquid. They also saw the net force (gray arrow) displayed on the object, which varied in direction. The size of these arrows changed in concordance with their representative forces as the user explored the simulation and manipulated the objects under investigation, exploring the various materials (i.e., cork, ice, and brick), varying their sizes, and changing the liquid's density (water, citric acid, and gasoline). Users could also see the mass and volume of the amount of water displaced by the object in a graduated cylinder on the screen. There was no audio feedback provided. There were no directions or text (aside from that associated with the user controls and mass and force readout) included in-simulation. An image of what the users saw and interacted with is shown in Fig. 2.

Our Guided-Inquiry Approach

Our HES for learning was designed to promote the integration of the subconcepts of density and buoyant forces, stressing the relationship between the object itself and the surrounding fluid. All subjects (40 undergraduate education majors) engaged in some initial exploration to familiarize themselves with the simulation's controls and the haptic device. They then completed a series of exercises (5) designed to guide their explorations, to help ensure that each user had the opportunity to consider the various factors that determine sinking and floating, and standardize their experiences in the simulation as best we could. We considered this approach and degree of scaffolding to be a guided-inquiry approach as described elsewhere (e.g., de Jong 2006; de Jong et al. 2013; de Jong and Van Joolingen 1998). "Appendix 1" includes these exercises.

In designing the exercises, we purposefully targeted interactions that we thought "felt good" (e.g., pushing a big cork into water) and had the potential to demonstrate each of the contributing factors that determine buoyancy. Exercise 1 targeted the idea that an object's mass is not the only reason why it sinks/floats. It addressed the common incomplete everyday idea that "heavy things float and light things sink" at the onset. It also introduced the contributing factor of volume. Exercise 2 (with ice cubes) was designed to help users see (and feel) that sinking/floating also depends (in part) on the relationship between the density of the object and the density of the liquid it is placed in. Exercise 3–5 (with a large cork in water) was used to draw users' attention to the centrality of water displacement in determining an object's buoyancy. It is important to note that we did not explicitly draw users' attention to the force arrows until these final three exercises. We viewed

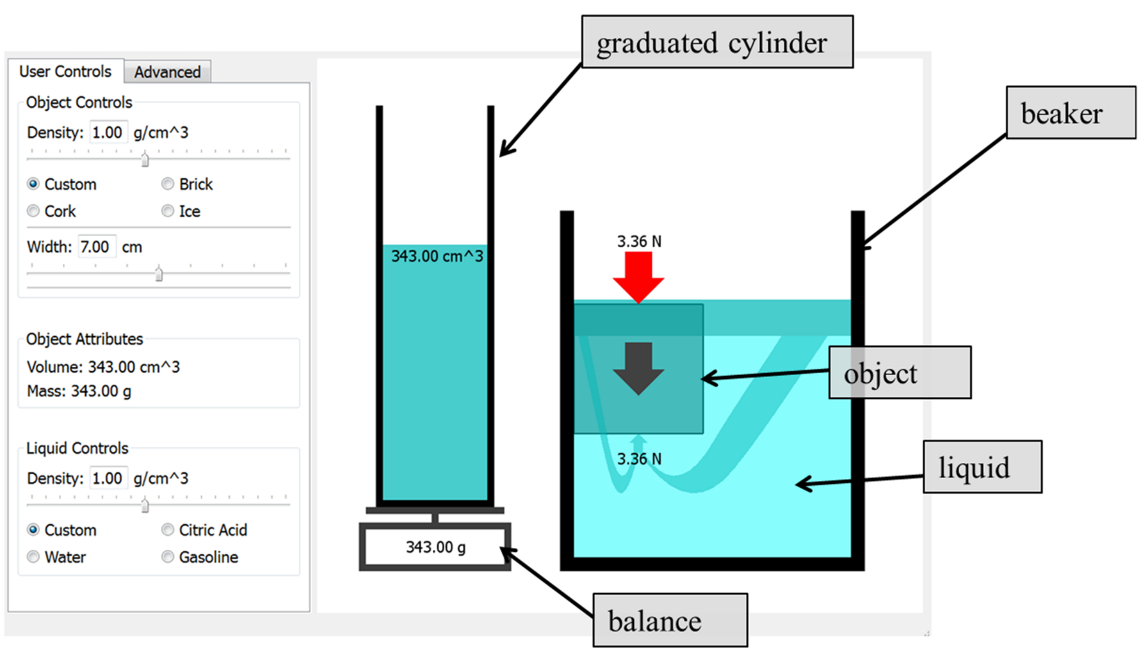


Fig. 2 A representative screenshot of our simulation for learning (labels added)

exercises 1–2 as “stepping stone” interactions (Wiser and Smith 2009). We believed that the recognition of the contributing factors (mass, size, shape, material) should be considered when reasoning about buoyancy before the underlying forces were introduced (Heywood and Parker 2001).

Study Details

The overarching research question in this exploratory study was: *How does haptic feedback influence users' understandings of buoyancy*. We adopted a research approach similar to some of our earlier work in this area (e.g., Minogue et al. 2006; Minogue and Jones 2009). A randomized pretest–posttest control group design was used. A convenience sample ($n = 40$) was drawn from the university's population of undergraduate education majors. Two main groups were formed from this sample population, haptic feedback ($n = 22$) and no haptic feedback ($n = 18$). All subjects except one were female. Most (92.5 %) were Caucasian, 5 % were Black, and 2.5 % were Asian. Both groups experienced the same core simulation described above and used identical interfaces (see Fig. 2). One group engaged with the HES and received bimodal feedback (visual + haptic). The other group (visual only) did not receive any force feedback. These conditions were achieved by incorporating a software switch that turns off the haptic feedback.

Protocol and Assessments

All participants followed the same study protocol individually. Total study time ranged between 43 and 78 min, with a mean study time of 58 min. Each participant:

- Completed a brief demographic (e.g., gender, ethnicity, and age) and efficacy survey
- Completed a *Why Things Sink and Float* (WTSF) prompt (Kennedy and Wilson 2007)
- Completed a four question close-ended (multiple choice) questionnaire
- Interacted with the simulation for learning
- Upon completion of the five in-simulation exercises, participants again completed the *Why Things Sink and Float* (WTSF) prompt mentioned above and an objective questionnaire, as post-assessments

General Analytic Approach

In this study, a mixed-methods approach was utilized to garner both quantitative and qualitative data regarding subjects' conceptions of buoyancy. We followed the triangulation design: data transformation model (transforming QUAL data into QUAN) depicted below in Fig. 3 (Creswell and Plano Clark 2007, p. 63).

Direct comparison of participants' gain scores (pretest–posttest differences) between the study's two treatment groups (haptic and no haptic) was made. In the next section, we describe each of the study's data sources and explain how the data from each measure were analyzed.

Data Sources and Their Analyses

Demographics and Efficacy

The demographic survey asked participants to identify their gender, ethnicity, and age. Participants were also able to voluntarily report their overall GPA at the time of the study. These data were analyzed using descriptive statistics. The brief efficacy survey included three efficacy questions that asked participants to consider their teaching of physical science concepts (chemistry, physics, and earth science) to elementary-aged students and rate their confidence on a four-point Likert scale (e.g., 1 = a bit worried, 2 = somewhat confident, 3 = confident, 4 = extremely confident). We chose not to ask about life sciences because this is commonly the content area with the highest efficacy scores. Descriptive statistics were used to analyze these data.

Open-Ended Question

The next measure, the *Why Things Sink and Float* (WTSF) prompt, asked participants to “Explain why things sink and float. Write as much information as you need to explain your answer. Use evidence and examples to support your explanation” (Kennedy and Wilson 2007). Pretest and posttest written responses to this were scored using the BEAR Assessment System's (BAS) progress variables scheme shown in “Appendix 2.” A progress variable is focused on the concept of progression or growth. It assumes that learning is not simply acquiring quantitatively more knowledge and skills but rather that learning progresses toward higher levels of competence as new knowledge is linked to existing knowledge and deeper understandings are developed from and take the place of earlier understandings. It is thought that the progress variables provide qualitatively interpreted frames of reference for particular areas of learning (buoyancy in the current work) and enable researchers to interpret levels of achievement in terms of the kinds of understandings typically associated with those levels (Kennedy and Wilson 2007). For the study described here, numbers were attached to each of the levels to quantify them and ease their

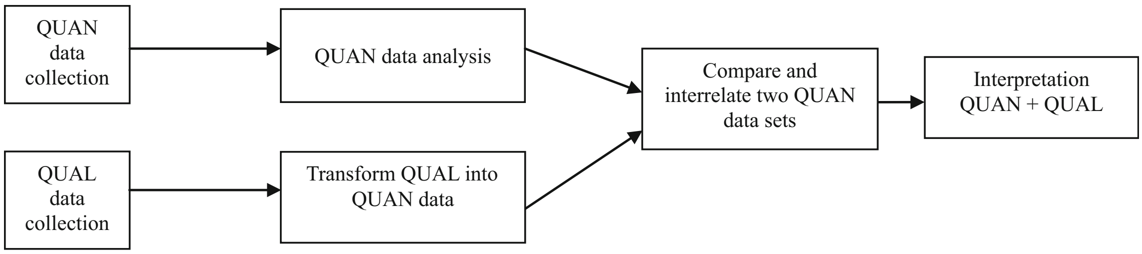


Fig. 3 A depiction of the mixed-methods approach used in the study

analyses. To investigate whether statistically significant differences existed between the two treatment groups, a simple gain score approach was employed. Difference scores were compared using independent *t* tests ($\alpha = .05$).

Closed-Ended Questions

Participants also completed a four (4) question closed-ended (multiple choice) questionnaire. Questions 1 and 2 asked about the definitions of density and buoyant force. Question 3 asked what determines whether an object will sink or float and Question 4 had participants interpret a picture of blocks floating in two different liquids (see "Appendix 3"). Again, total scores were calculated and a direct comparison of the two groups (haptic and no haptic) was made using a gain score approach with independent t tests.

Content Analysis

Finally, subjects' written responses to the WTSF prompt were further analyzed using summative content analysis (Hsieh and Shannon 2005). Here key terms and their part of speech were identified and counted in the manifest content. Quantizing, or transforming the qualitative data into numerical codes (in this case frequency counts), aided in the identification of patterns and helped maintain some analytic integrity. The results of this content analysis are represented using descriptive statistics.

Results

Efficacy

Table 1 captures the study sample's demographic data and self-reported self-efficacy regarding the teaching of chemistry, physical science, and earth science content, respectively. All the values in Table 1 are the means (*M*). For chemistry efficacy, responses ranged from 1 to 3 with a mode of 2 across both treatments. Participants' physical science efficacy across treatments ranged from 1 to 4 with a mode of 2. Earth science efficacy also ranged from 1 to 4, but the mode was 3 (confident). These data suggest that the two treatment groups were comparable. It is also interesting to note the higher efficacy scores for the teaching of earth science content.

Table 1 Demographic and efficacy data

	Visual only	Visual + haptic
Age	20.7	20.6
GPA	3.67	3.58
Chemistry efficacy	1.9	1.9
Physical science efficacy	1.8	2.0
Earth science efficacy	2.9	2.7

Four-point Likert scale (*1* a bit worried, *2* somewhat confident, *3* confident, *4* extremely confident)

Gain Scores

Table 2 shows the results of the independent t tests ($\alpha = .05$) that were conducted using the gain scores on two different measures (the WTSF prompt and the objective questionnaire). While no significant differences were found across the treatment groups, small effect sizes can be seen both measures. We suspect that the WTSF rubric was not sensitive enough to accurately catalog the responses of the study's sample. Designed for the use with younger students, the mean scores for both groups were near the ceiling of 7 (5.6 for visual only and 6.0 for visual + haptic pretest; 6.2 for visual only posttest and 5.55 for visual + haptic posttest).

Differences in Term Use

Despite the findings of no statistically significant differences between the treatment groups' pre-to-post responses to the WTSF prompt, the summative content analysis (Hsieh and Shannon 2005) revealed some interesting trends across the treatment groups. Figure 4 shows the frequency distribution of different *adjectives* found in subjects'

Table 2 Comparison of scores across treatment groups

Measure	Visual only ($n = 20$)		Visual + haptic ($n = 20$)		*Df*	*t*	*p*	95 % CI		Effect size (Cohen's *d*)
	M	*SD*	*M*	*SD*				Lower	Upper	
Pretest WTSF Prompt[a]	5.60	1.46	6.00	1.41						
Posttest WTSF Prompt	6.20	1.78	5.55	1.94						
Gain WTSF Prompt	0.60	1.47	−0.10	1.94	38	1.23	.206	−0.40	1.80	0.41
Pretest multiple-choice questions[b]	3.40	0.58	3.55	0.60						
Posttest multiple-choice questions	3.50	0.50	3.50	0.59						
Gain multiple-choice questions	0.10	0.72	−0.05	0.67	38	0.68	.504	−0.30	0.60	0.21

[a] Scores ranged from 0 to 7

[b] Scores ranged from 0 to 4

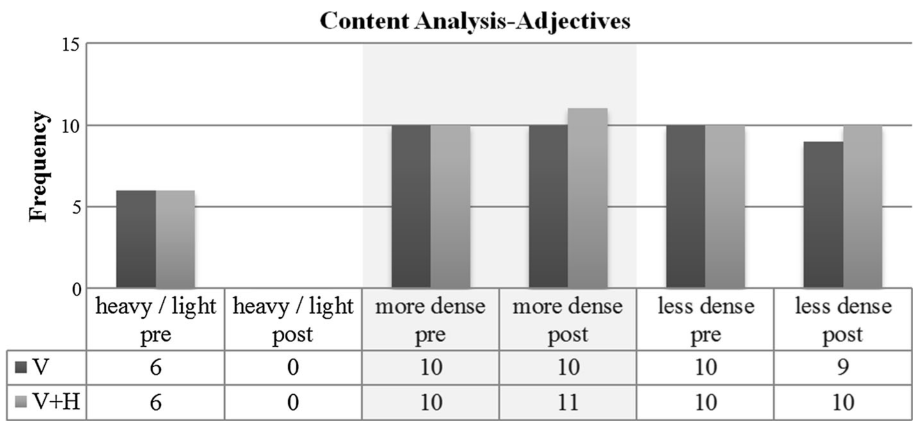


Fig. 4 The summative content analysis of adjectives found in subjects' responses across treatment groups

responses. It can be seen that the use of these adjectives varied very little across treatments, i.e., their descriptions of the observed phenomena were quite similar. This suggests that the addition of haptic force feedback did not really influence how the participants described the sinking/floating phenomena.

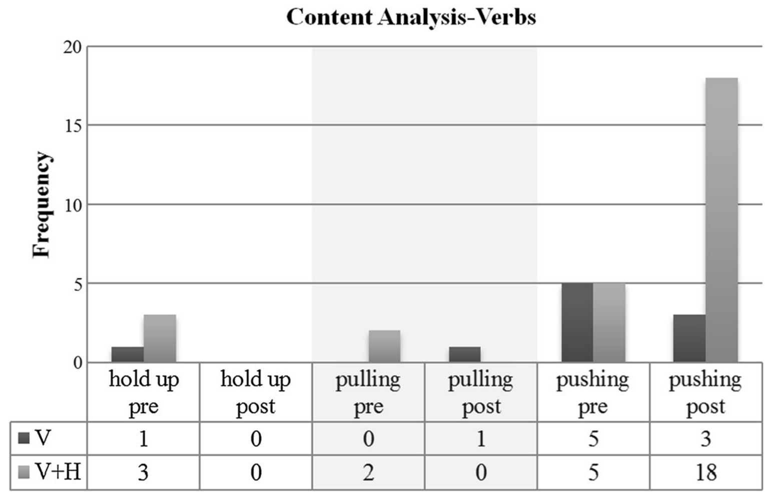
However, when we looked at the verbs that were used across treatments (Fig. 5), we can see a marked difference in the posttest use of the *pushing* term in the visual + haptic group. This finding suggests that users receiving haptic feedback were sensitive to the pushing up of the buoyant force that was modeled. Interestingly, users only thought of the haptic interaction in terms of "pushing," and we do not see the effect on the pull of the gravitational force which suggests that users did not think about buoyancy in terms of forces in action (opposite and opposing forces). An alternative explanation is that the visual feedback of a sinking block was enough for users to appreciate what was happening.

Figures 6 and 7 both illustrate the frequency distribution of *nouns* found in subjects' written responses to the WTSF prompt.

A striking pretest–posttest difference can be seen in the use of terms like *force*, *net force*, *gravity*, *buoyant force*, and *water displacement* for the subjects in the visual and haptic group, while the visual only group's use of these terms remained static (and relatively lower). These nouns were used as the "thing" that caused the observed result (sinking or floating). This increase in the use of nouns after receiving the force feedback may be a signal that haptic users more readily pointed to the mechanisms for the phenomena, a step beyond phenomena-based reasoning to relation-based reasoning (Driver et al. 1996). We discuss this further in "Discussion" section.

Figures 8 and 9 show a couple of representative examples of subjects' pre–post written responses; both examples are from the visual and haptic condition. We hope that readers can appreciate the qualitative differences in the pre–post responses, in particular, the incorporation of forces in their explanations and increased attention to the relationships among the contributing factors as the mechanism underlying the observed phenomena.

Fig. 5 The summative content analysis of verbs found in subjects' responses across treatment groups



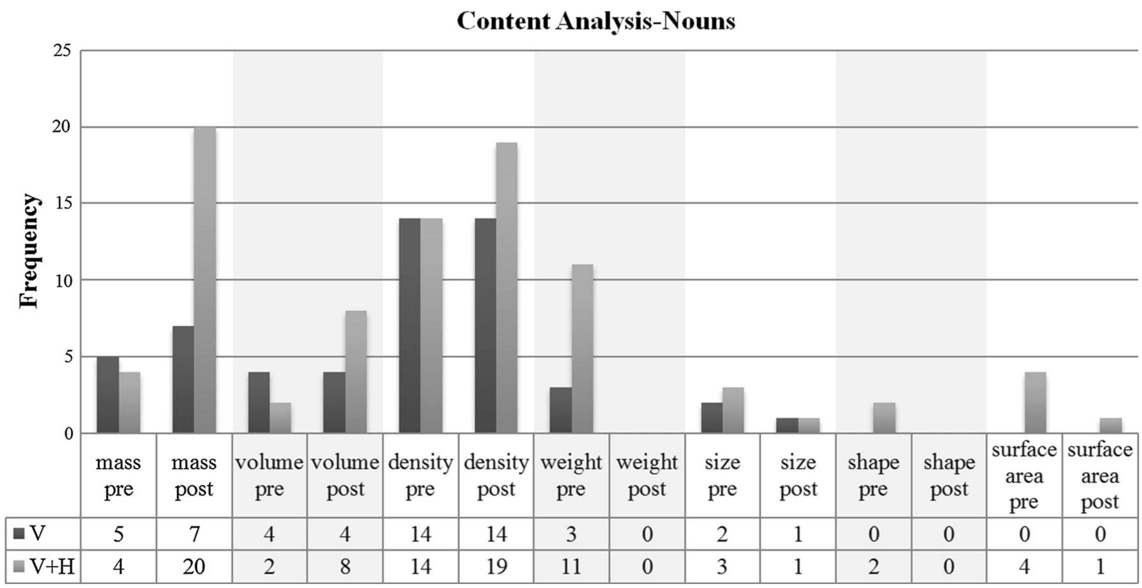


Fig. 6 The summative content analysis of nouns found in subjects' responses across treatment groups

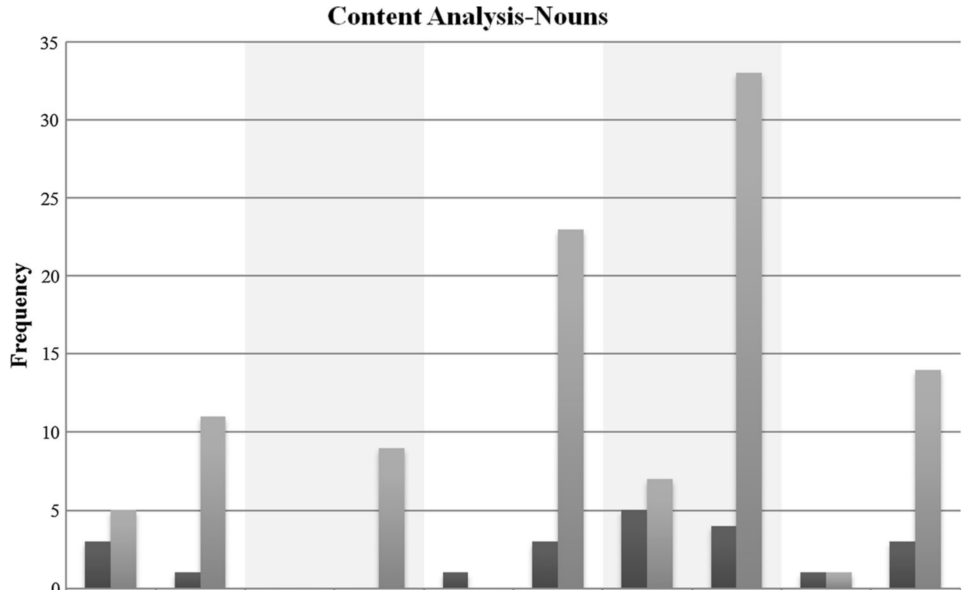
Discussion

No Significant Differences, but Practical Differences

The exploratory work chronicled here tested a haptically enhanced simulation (HES) for learning about buoyancy and adopted a mixed-methods approach to add to the growing research based on haptics in science education. While potentially a breakthrough technology for instructional simulation environments, it has proven difficult for the research community to tease out the differential impacts of haptics (assuming they exist). This problem persisted in our study. As shown in Table 2, the quantitative analyses using a gain score approach resulted in no significant differences across the treatment groups on two different measures. This is has become a rather common finding of the studies conducted in this area. Work in this arena is still quite young, and there is a critical need for more systematic investigations of how individuals perceive, process, store, and make use of haptic information in multimodal learning environments. This makes our work important from a research perspective.

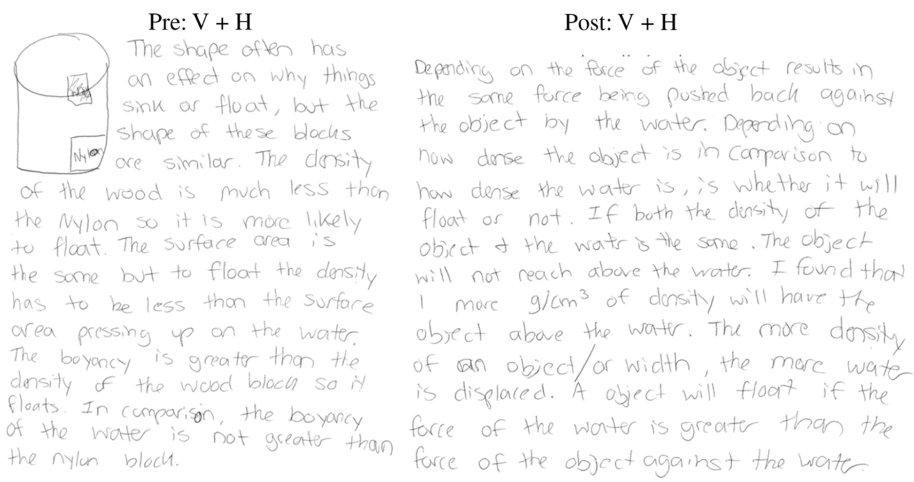
One possible explanation for this consistent finding is that students are traditionally presented information and science concepts using visual stimuli alone. Klatzky et al. (1993) proposed two serial models for the initiation of haptic exploration that support and build on the idea of the "visual capture" of object properties, but we think these models of action and perception should be extended to

Fig. 7 The summative content analysis of more nouns found in subjects' responses across treatment groups



	force pre	force post	net force pre	net force post	gravity pre	gravity post	buoyant force pre	buoyant force post	water displacement pre	water displacement post
■ V	3	1	0	0	1	3	5	4	1	3
■ V+H	5	11	0	9	0	23	7	33	1	14

Fig. 8 A representative example of a qualitative shift in student responses



include phenomena (not just properties). Their *Visual Dominance* model (Fig. 10) suggests that visual analysis is exhausted before any haptic exploration is initiated. If ample information can be gained through vision alone, the force feedback may not be salient to the person. The *Visual Preview* model includes a brief visual analysis resulting in a response if adequate information is obtained. If more information is needed, the individual may pick up on additional information visually or even become more sensitive to the haptic feedback being provided and use that in their reasoning. Considering these models, we suspect that the additional perceptual information made available through haptic exploration was never fully capitalized on by the users in this study when they completed the traditional paper–pencil assessments.

A more practical explanation of the observed results may be the nature and format of the assessment tasks that we used. It is reasonable to argue that the written paper and pencil cognitive assessment items did not fully capture the learning/performance differences that may have existed between the treatment groups. It is not until we undertook a finer-grained qualitative analysis of the subjects' written responses to the WTSF prompt (using content analysis) that signals of treatment differences

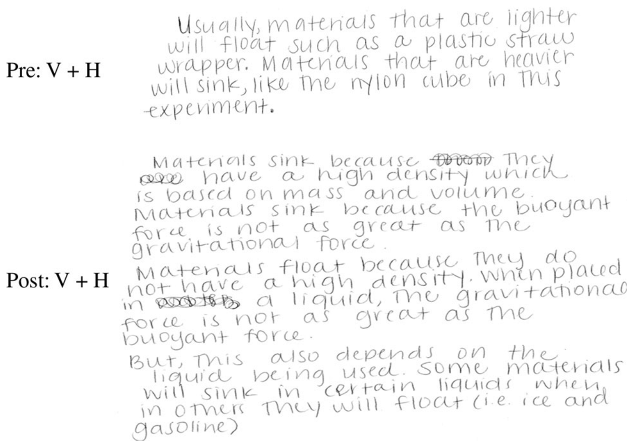


Fig. 9 Another representative example of a shift in student responses

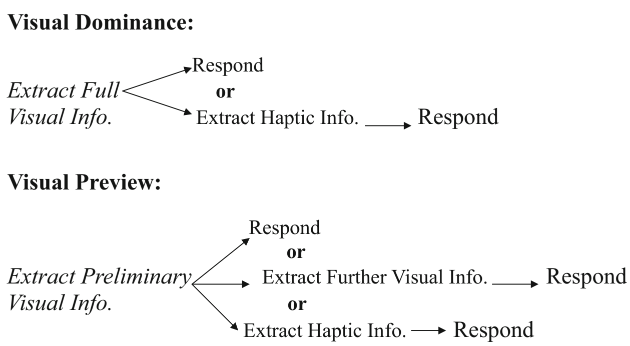


Fig. 10 Klatzky et al. (1993) models representing the haptic exploration of objects in the presence of vision

emerged. Such findings underscore the value of mixed-methods designs.

This work presents preliminary evidence that adding haptic feedback (simulated touch) to a simulation for learning influenced users' thinking about sinking and floating. Driver et al. (1996) developed a "portrayal of students' views of the nature and status of scientific knowledge by categorizing their responses to a series of probes" (p. 112). Their framework is described as a general typology of the relationship between description and explanation (and ultimately reasoning). Their framework identified qualitatively distinct epistemological explanations/representations. *Phenomenon-based* explanations are characterized by a focus on surface characteristics of phenomena. These explanations are re-descriptions of the observed phenomenon; often explanation and description are not distinguished. In our study, we found no real difference in the adjectives that users used in the WTSF responses (descriptions of why things sink or float), suggesting that *phenomenon-based reasoning* was unaffected.

However, we did find that learners afforded haptic force feedback made more frequent use of terms like *push*, *force*, *net force*, *gravity*, *buoyant force*, and *pushing*. Subjects that had access to the haptic feedback also seemed more able to take up and use the idea of *water displacement* and the critical role that water displacement plays in sinking and floating. We suggest that this sort of term use serves as a marker for *relation-based reasoning*.

Epistemologically, this type of reasoning moves beyond *phenomenon-based* explanations to include attention to relationships between/among variables/conditions. Here empirical generalizations and/or linear causal reasoning is made, and underlying mechanisms for the sinking/floating phenomena are suggested. These findings suggest that haptic users were able to overcome some of the conceptual shortcomings described by Loverude et al. (2003), namely the inability to recognize the factors that govern the magnitude of buoyant forces, despite knowing the buoyancy formula, and the failure to consider the role of displaced volume of liquid when trying to determine the buoyant force. These findings have practical importance in science education, as Heywood and Parker (2001) have suggested that students rarely think of floating and sinking as forces in action. Our findings suggest that the addition of simulated force feedback might start learners down the road to more complete reasoning about and explanations of complex science content.

Theoretical Importance

A main thrust of the exploratory work reported here was to lay the groundwork for a more inclusive cognitive model, one that can help describe how learners integrate and use visual and haptic information in multisensory learning environments. Theoretically, we think that the observed difference in term use is early evidence that incorporating the simulated sense of touch (haptic feedback) impacts the way in which learners *perceive*, *attend to*, and *select* information for further processing. The work presented here builds on an earlier study by Han and Black (2011), honing in on embodied cognition as a way to isolate and describe the influences of haptic feedback, underscoring the importance of dynamic interactions between the body and the physical world in the meaning-making process (Barsalou 2008; Barsalou et al. 2003; Gibbs 2005; Glenberg 1997; Lakoff and Johnson 1999). Our study suggests that multimodal mental representations and corresponding explanations created by physical interactions may serve as a cognitive grounding for understanding abstract, hard to learn, but foundational physics concepts like force.

Language-Mediated Haptic Cognition?

Although the findings from this study are preliminary, such early evidence may lead to the development of a theory and framework for studying *language-mediated haptic cognition*. A novel theory builds on the idea of semiotic schemas (Roy 2005a, b; Roy and Reiter 2005), a framework born out efforts to construct robotic and virtual systems that connect situated language to machine action and perception. Semiotic schemas stress the importance of "grounded" verbs, adjectives, and nouns which refer to physical referents using a unified representational scheme. In a cycle that relies on both "bottom-up" sensor-grounded perception and "top-down" action on the physical environment, individuals are able to build conceptions of complex events, objects, and object properties.

Such assertions may seem like an overstatement of the obvious to some readers. That is to say, one may not be surprised that subjects receiving haptic feedback used more haptically grounded terms (*force*, *net force*, *gravity*, *buoyant force*, and *pushing*) compared to subjects that did not receive haptic feedback, but readers are urged to look beyond the surface logic of this finding. Such differences provide some signals that users did actually *attend to* the haptic feedback being provided in the HES and even more importantly *drew upon* this sensory information as they provided written descriptions of buoyancy. This preliminary evidence is a critical first step in unraveling the cognitive impact of this technology and may even begin to lend credence to the philosophical and theoretical claims that have been made about the embodied nature of concepts (e.g., Barsalou 2008; Gibbs 2005; Reiner 1999) and the critical role that touch plays in the meaning-making process.

Limitations and Future Work

The results of this exploratory work are limited due in part to its small and narrow sample; only 40 subjects (with only one male and few minorities) drawn from a single program at just one institution. Cleary, this hampers the generalizability of this work. Additionally, as mentioned earlier, our paper–pencil assessments may not have been sensitive to the influence of simulated touch on cognition.

Ideas for future work, born out of this initial study, center on gathering more evidence of our emerging theory of *language-mediated haptic cognition* in other contexts. This includes the testing of this HES for learning with other populations; of particular interest is upper elementary students. It might also be interesting and informative to assess users' understandings of forces, perhaps using the established *Force Concept Inventory* (Hestenes et al. 1992), to better understand how they think about forces and how haptic feedback influences understandings.

This work has the potential to advance our understandings of the nature and functioning of haptic cognition. Its content analysis using grounding terms represents a potentially useful way to assess student learning in haptically augmented virtual learning environments. Current difficulties regarding the accurate assessment of student learning in virtual learning environments are due in part to the complicated interconnections among words, internal representations, and physical environments. The power of this exploratory work lies in its ability to shed light on this issue by providing early evidence that *language mediates haptic cognition*. Written language is commonly viewed as an indispensable psychological tool that can bridge the gap between lower and higher mental functions (Kozulin 1990; Vygotsky 1978). We put forward that *haptically grounded* words function as pointers to concepts in the mind and that these concepts are fundamentally different than ones formed form visual and verbal information alone. Further refinement and use of this diagnostic approach may help researchers gather much-needed empirical data that can be used to support or refute the numerous philosophical and theoretical claims being made about the pedagogical power of incorporating haptics into the teaching of school science.

Appendix 1: Guided-Inquiry Prompts

Investigating Students' Ideas about Buoyancy Simulation for Learning Exercises

Exploration

(a) Spend some time exploring the interface and familiarize yourself with its functionalities. Remember to **press and hold the round button** on the device to **grab the objects**.

- Adjust the various ***Object Controls*** including the **Density** and **Width sliders**.
- Try using the **Density Sliders** in the ***Liquid Controls***.

Be sure to take notice of how the ***Object Attributes*** (volume and mass) change as you move these sliders. Also pay attention to the volume and mass of the **water being displaced** and the **forces being displayed**.

(b) Experiment with **various combinations of Objects and Liquids**. Observe what happens.

Exercise 1

Select "Custom" in the ***Object Controls*** and "Water" in the ***Liquid Controls***. Adjust the **Density** slider for the object.

- What is the relationship between the object's density and its mass given a constant volume (i.e., width)?
- What happens to the mass of the object if you adjust its volume/width? Does the density change?

Exercise 2

Select "Ice" in the ***Object Controls*** and keep the ***Liquid Controls*** on "Water."

- What do you notice about the density of the ice cube and the density of the liquid? Does the ice sink or float?
- What happens when you submerge the ice cube (grab it by using the round button on the device) and let it go?
- What happens if you adjust the **Width** slider in the ***Object Controls***?
- Can you change the type of liquid (***using the Liquid Controls***) to make ice sink? Why did the ice sink?

Exercise 3

Select "Cork" in the ***Object Controls*** and set the ***Liquid Controls*** back on "Water." Set the object's width at 6.00 cm.

Press the button on the haptic device to grab and place the cork in the water. What do you notice about the **forces being displayed** and the **amount of water being displaced**?

Now move the **Width slider** over to 8.00 cm. Again, press the button on the haptic device to grab and submerge the cork. How does this impact the **forces being displayed** and amount of **water displaced**?

Exercise 4

Select "Brick" in the ***Object Controls*** and keep the ***Liquid Controls*** on "Water." Grab the brick block and place it in the water. Keep hold of it with the button.

- What do you notice about the **mass of the displaced water** in relation to the **mass of the object**?
- What do you notice about the **magnitude of the displayed forces**?
- Adjust the width of the brick block and submerge it. How does this impact the relationship between the **mass of the displaced water** and the **mass of the object**?

Exercise 5

Find an object that floats in water. Grab it and submerge it.

- What do you notice about the **mass of the displaced water** in relation to the **mass of the object**?
- What do you notice about the **magnitude of the displayed forces**?
- Adjust the width of the object and submerge it. How does this impact the relationship between the **mass of the displaced water** and the **mass of the object**?

Appendix 2

See Table 3.

Table 3 *Why Things Sink and Float* (WTSF) assessment scheme

Level	What the student already knows		What the student needs to learn
RD (7)	*Relative Density*		
	Student knows that floating depends on having less density than the medium		
	"An object floats when its density is less than the density of the medium"		
D (6)	*Density*		
	Student knows that floating depends on having a small density		To progress to the next level, student needs to recognize that the medium plays an equally important role in determining if an object will sink or float
	"An object floats when its density is small"		
MV (5)	*Mass and Volume*		
	Student knows that floating depends on having a small mass and a large volume		To progress to the next level, student needs to understand the concept of density as a way of combining mass and volume into a single property
	"An object floats when its mass is small and its volume is large"		
M or V (4)	*Mass*	*Volume*	
	Student knows that floating depends on having a small mass	Student knows that floating depends on having a large volume	To progress to the next level, student needs to recognize that changing EITHER mass OR volume will affect whether an object sinks or floats
	"An object floats when its mass is small"	"An object floats when its volume is large"	
PM (3)	*Productive Misconception*		
	Student thinks that floating depends on having a small size, heft, or amount, or that it depends on being made out of a particular material		To progress to the next level, student needs to refine their ideas into equivalent statements about mass, volume, or density. For example, a small object has a small mass
	"An object floats when it is small"		
UF (2)	*Unconventional Feature*		
	Student thinks that floating depends on being flat, hollow, filled with air, or having holes		To progress to the next level, student needs to refine their ideas into equivalent statements about size or heft. For example, a hollow object has a small heft
	"An object floats when it has air inside it"		
OT (1)	*Off Target*		
	Student does not attend to any property or feature to explain floating		To progress to the next level, student needs to focus on some property or feature of the object in order to explain why it sinks or floats
	"I have no idea"		
NR (0)	*No Response/Unscorable*		
	Student left the response blank or gave a response, but it cannot be interpreted for scoring		To progress to the next level, student needs to respond to the question

Appendix 3: Close-Ended Questions

Please answer each of the below questions by circling the correct response.

Density is defined as:

(a) mass multiplied by volume
(b) volume divided by mass
(c) mass divided by volume
(d) weight multiplied by volume

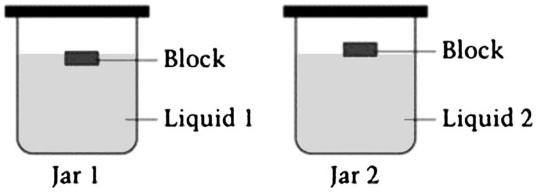
The supporting force exerted by a fluid on an object immersed in it is called __________.

(a) buoyant force
(b) viscosity
(c) lift
(d) density

What determines whether an object will sink or float?

(a) whether the buoyant force is larger than the object's mass
(b) whether a buoyant force acts on the object
(c) the direction of the buoyant force on the object
(d) whether gravity acts on the object in the fluid

Look at the two pictures below. They show what happened when two solid blocks were each put in a jar containing a liquid. Based just on what you can see in the pictures, what can you say about the blocks and the jars?



1. The liquid in the jars must be water.
2. The block in jar 1 weighs more than the block in jar 2.
3. The block in jar 1 is floating lower in its liquid than is the block in jar 2.
4. The block in jar 1 must be made of metal, and the block in jar 2 must be made of wood.

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