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

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Introduction

As humans we commonly (and seemingly effortlessly) use our hands to learn about the world around us as we use sensory information gained through touch to build our understandings of complex objects and events. Relatively recent advances in technology have made the addition of "touch" to computer-generated virtual environments possible. While potentially a breakthrough technology for instructional simulation environments, there is little research to guide instructional designers. There is a burgeoning research base on haptics but touch remains an understudied and perhaps underutilized sensory modality in the creation of computer-mediated instructional programs.

What is Haptics?

The word "haptic" is derived from the Greek terms *haptesthai* which translates to *able to lay hold of* and *haptikos* meaning *able to touch* (Revesz, 1950; Katz, 1989). Current uses of the term most often refer to the study of touch and the human interaction with the external environment via touch. Haptically augmented multimodal interfaces can be programmed to provide realistic force feedback (e.g. simulating object compliance, weight, and inertia) and/or tactile feedback (e.g. simulating surface contact geometry, smoothness, slippage, and temperature) by employing physical receptors in the hand and arm that gather sensory information as users "feel" and manipulate two and three-dimensional virtual objects and events (Jacobson, Kitchen, & Golledge, 2000).

Point-probe devices like the one used in the present study tracks the x, y, and z coordinates, as well as the pitch, roll, and yaw of the virtual point-probe that the user moves about a 3D workspace. Actuators (motors within the device) communicate preprogrammed forces back to the user's fingertips and arm as it detects collisions with the virtual objects rendered, simulating the sense of touch.

Haptics in Education

The idea of a hands-on minds-on curriculum is not a new one. An emphasis on actively involving students in learning has influenced American schools throughout its history. Early advocates, such as John Dewey, suggested that this mode of instruction was indispensable (Dewey, 1902, p. 20). The theoretical claims surrounding the potential impact of haptics in education are many (e.g. McMurray, 1921; Piaget, 1954; Fitts & Posner, 1967; Wadsworth, 1989; Reiner, 1999; Williams, et al., 2003). Some suggest that the addition of haptics affords student users the opportunity to become more fully immersed in this meaning-making process, leading to more connected and more robust understandings. Others contend that haptic feedback conjures up experiential or embodied knowledge that would otherwise lie untapped in the recesses of our long term memory.

While there is some surface logic of the positive benefits of haptic technology in education, existing research literature does not provide a clear answer to its efficacy. Despite a voluminous literature base from the fields of developmental and cognitive psychology (e.g. Heller, 1991; Loomis & Lederman, 1986; Klatzky & Lederman, 2002) regarding underlying principles and processes of the haptic perception and cognition, very little is known about the true educational impact of haptic technology (Author, 2006a). This is due largely in part to the fact there are only a handful of studies (e.g. Author, 2003, 2006a, 2006b; 2009; Florence et al., 2004; Reiner, 1999; Williams, Chen, & Seaton, 2003) that have examined the use of haptic interfaces within the context of teaching and learning.

This article describes the testing of a haptically-enhanced simulation for learning. Informed by earlier studies in science education and the cognitive sciences, the learning environment will target the core science content that one needs to build a sound understanding of the concept of *buoyancy*.

Defining the Arena

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). 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' and 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): density, fluid, force, gravity, mass, weight, and buoyancy?.

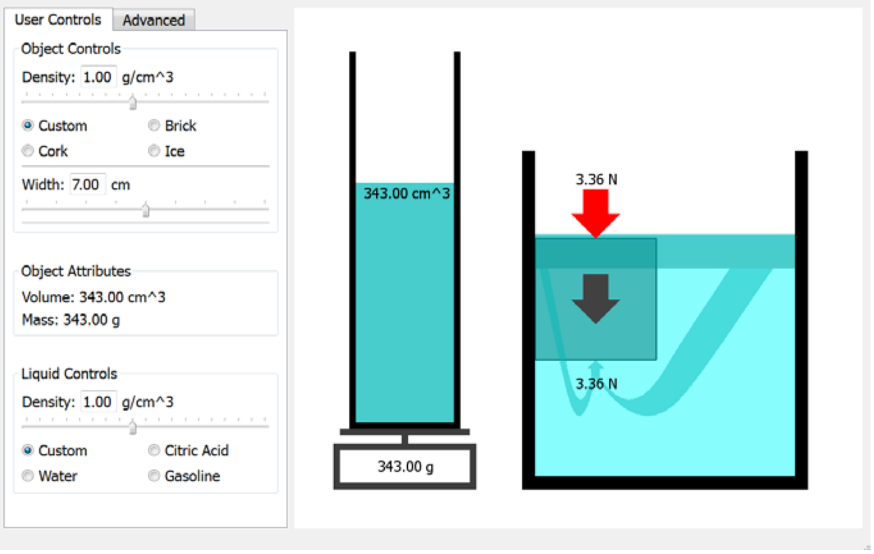
Prior studies of children's thinking about buoyancy (e.g. Ginns & Watters, 1995; Halford, Brown, & Thompson, 1986; Hardy, Jonen, Möller, & Stern, 2006; Kohn, 1993) suggest that novices often focus on only one dimension of the sinking and floating phenomenon. Our simulation promotes the integration of the sub-concepts of *density* and *buoyant forces* and stresses the relationship between the object itself and the surrounding fluid.

Methods

Our Interface

Although still on the fringe of classroom learning technologies, haptics (simulated touch) has the potential to radically change the way in which learners interact 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. Our haptically-enhanced simulation (shown in Figure 1) for learning allows users to:

- directly compare (and feel) the densities of the object(s) and the surrounding liquid(s)
- feel the gravitational and buoyant forces associated with the sinking and floating of objects
- visualize the mass of the amount of water displaced by an object(s)



Object Controls
Density: 1.00 g/cm^3
● Custom ○ Brick
○ Cork ○ Ice
Width: 7.00 cm

Object Attributes
Volume: 343.00 cm^3
Mass: 343.00 g

Liquid Controls
Density: 1.00 g/cm^3
● Custom ○ Citric Acid
○ Water ○ Gasoline

Figure 1. A representative screen-shot of our simulation for learning.

Study Details

The overarching research question is: *How does haptic feedback influence users' understandings of buoyancy*. A randomized pre-test-post-test control group research 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). Both groups experienced the same core VLE (described briefly above) and use identical interfaces (Figure 2). One group received bi-modal feedback (visual + haptic) and the other group did not (visual only). These conditions are achieved by incorporating a software switch that turns off the haptic feedback.

The haptic device of choice is Novint Technologies, Inc. Falcon (http://www.novint.com/). This point-probe haptic interface (Figure 2) is able to track 3-DOF (x, y, and z coordinates) in the computer generated virtual environment and provided force feedback corresponding to these movements.

Figure 2. The Novint Falcon

Participants followed the below study protocol individually. Total study time ranged between 43 and 78 minutes, with a mean study time of 58 minutes. Each participant:

- Completed a brief demographic (e.g. gender, ethnicity, age) and efficacy survey
- Completed a *Why Things Sink and Float* (WTSF) prompt.

- Completed a concept mapping task.
- Completed a four (4) question close-ended (multiple choice) questionnaire.
- Interacted with the simulation for learning. After some initial unconstrained exploration, participants completed a series of exercises (5) designed to guide and standardize their experiences in the virtual learning environment. See Appendix for these exercises.
- Upon completion of the five in-simulation exercises, participants completed the above described *Why Things Sink and Float* (WTSF) prompt, concept mapping task, and objective questionnaires as post-assessments.

In this study a mixed-methods approach was utilized to garner both quantitative and qualitative data regarding subjects' conceptions of buoyancy. Following a data transformation model (Creswell & Plano Clark 2007) qualitative data was collected, analyzed, transformed into quantitative data, and these data were merged during the interpretation. Figure 3 illustrates this mixed methods approach.

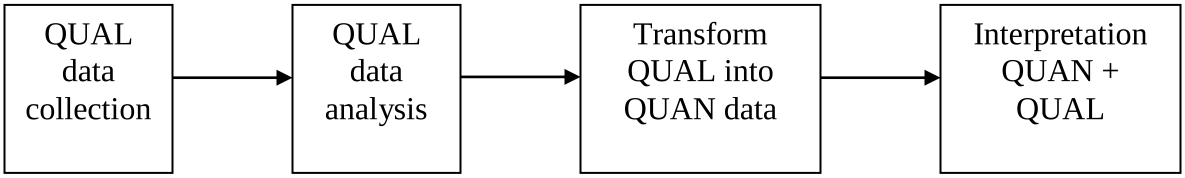


Figure 3. A depiction of the mixed-methods approach used in the study.

Direct comparison of participants' gain scores (pretest-posttest differences) between the study's two treatment groups (haptic and no haptic) were made. Additionally, as subjects' are engaged in the VLE the researcher will record *observables*, words (i.e., what users say) and actions (i.e., what users do) (Eisner, 1981; Minogue & Jones, 2009). In the next section I describe each of the study's data sources and explain how the data from each measure were analyzed.

Data Sources and Analyses

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 consider their teaching of physical science concepts (chemistry, physics, and earth science) to elementary aged student and rate their confidence on a four point Likert scale (e.g. 1= a bit worried, 2= somewhat confident, 3= confident, 4= extremely confident). Again, descriptive statistics were used to analyze these data.

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 & Wilson, 2007). Pretest and posttest written responses to this were scored using the BEAR Assessment System's (BAS) progress variables scheme shown below in Figure 4.

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 towards 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 allow researchers to interpret levels of achievement in terms of the kinds of understandings typically associated with those levels (Kennedy & Wilson, 2007). For the study described here, numbers were attached to each of the levels to quantify the levels and ease their analyses.

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. • "An object floats when its density is small."	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.
MV (5)	**Mass and Volume** Student knows that floating depends on having a small mass and a large volume. • "An object floats when its mass is small and its volume is large."	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.
M or V (4)	**Mass** Student knows that floating depends on having a small mass. • "An object floats when its mass is small." **Volume** Student knows that floating depends on having a large volume. • "An object floats when its volume is large."	To progress to the next level, student needs to recognize that changing EITHER mass OR volume will affect whether an object sinks or floats.
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. • "An object floats when it is small."	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.
UF (2)	**Unconventional Feature** Student thinks that floating depends on being flat, hollow, filled with air, or having holes. • "An object floats when it has air inside it."	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.
OT (1)	**Off Target** Student does not attend to any property or feature to explain floating. • "I have no idea."	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.
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.

Figure 4. The *Why Things Sink and Float* (WTSF) progress variable scoring scheme used.

To investigate if statistically significant differences existed between the two treatment groups a simple gain score approach was employed. Difference scores were compared using with independent t-tests (alpha = .05).

The concept mapping task stated, “In the space below construct a concept map of the following terms: buoyant force, density, displaced liquid, gravity, mass, sink/float, volume. Be sure to include linking terms that succinctly describe how the terms are related (see the example)”. Analyses of the concept maps created involved two levels. Level one analyses simply determined if the maps created were network or hierarchical in nature. Results of this are presented descriptively. Level two analyses used a relational scoring method with a criterion or model map (McClure, Sonak, & Suen, 1999; West, Park, Pomeroy, & Sandoval, 2002). Concept-links, cross-links, and examples were assessed using the following scale:

- invalid relationship between concepts (0 points);
- valid relationship between concepts but propositional label is incorrect (1 point);
- valid relationship and propositional label correct but lacks foundational or core relationship to subject matter (2 points), and
- valid relationship and propositional label and foundational or core relationship apparent (3 points).

Each link was scored separately and the scores added together to generate a total relational score for each map. Direct comparison of the data from the two groups (haptic and no haptic) was made using a gain score approach with independent t-tests.

Participants also completed a four (4) question close-ended (multiple choice) questionnaire. Questions #1 and 2 asked about the definition 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. 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.

Finally, subjects’ written responses to the WTSF prompt were further analyzed using summative content analysis (Hsieh & Shannon, 2005). Here key terms were identified and counted in the manifest content. ‘Quantitizing' 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 were represented using descriptive statistics.

Preliminary Findings

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. This data suggests 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)		

Table 2 shows the results of the independent t-tests (alpha = .05) that were conducted using the gain scores on three different measures (the WTSF prompt, the concept mapping task, and the objective questionnaire). While no significant differences were found across the treatment groups, small effect sizes can be seen on all three measures.

Table 2
Comparison of Mean Gain Scores Across Treatment Groups

	Visual Only (*n* = 20)			Visual + Haptic (*n* = 20)					95% CI		Effect Size (Cohen's *d*)
Measure	*M*	*SD*		*M*	*SD*	*Df*	*t*	*p*	Lower	Upper	
WTSF Prompt[a]	0.60	1.47		-0.10	1.94	38	1.23	**.206**	-0.40	1.80	0.41
Concept Mapping Task[b]	-0.15	2.60		0.95	4.08	38	-1.02	**.316**	-3.29	1.09	0.32
Multiple Choice Questions[c]	0.10	0.72		-0.05	0.67	38	0.68	**.504**	-0.30	0.60	0.21

[a] Scores ranged from 0-7
[b] Scores range from 0-18 based on a model map
[c] Scores ranged from 0-4

Although not part of the original analyses plan it was interesting to see that, despite being shown an example of a hierarchical concept map, there was quite a bit of variation in the types of concept maps students created (figure 5).

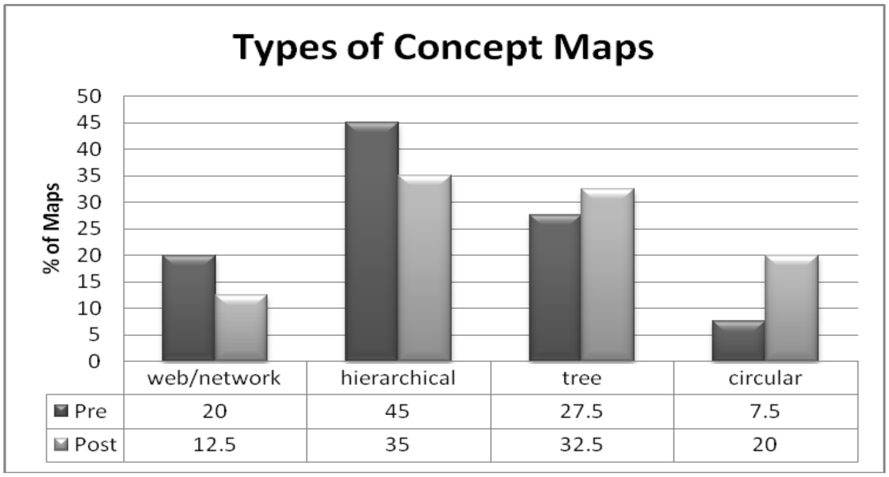


Figure 5. The variety of concept map types produced.

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 & Shannon, 2005) revealed some interesting trends across the treatment groups. Figure 6 shows the frequency distribution of different adjectives found in subjects' responses. It can be seen that the use of these adjectives varied very little across treatments. Similarly, figure 7 depicts the verbs that were used. Here one can see a marked difference in the post-test use of the *pushing* term in the visual + haptic group.

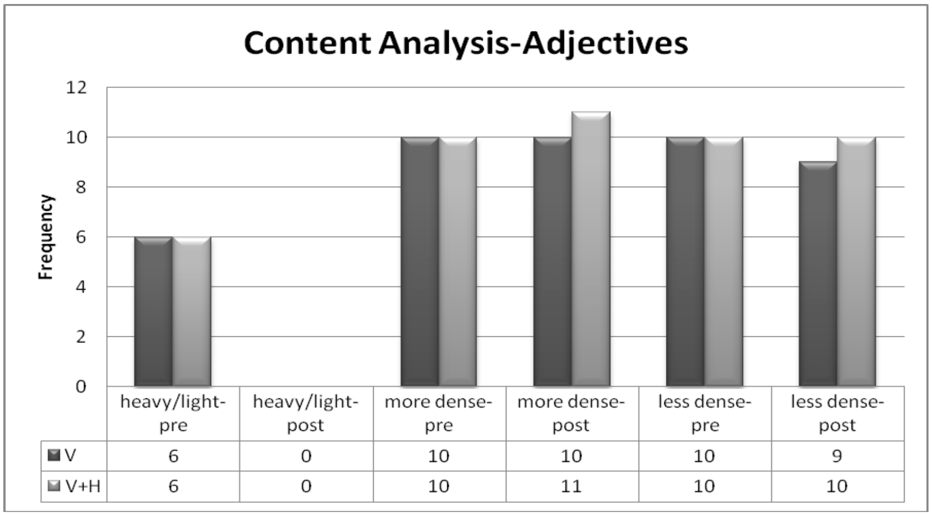
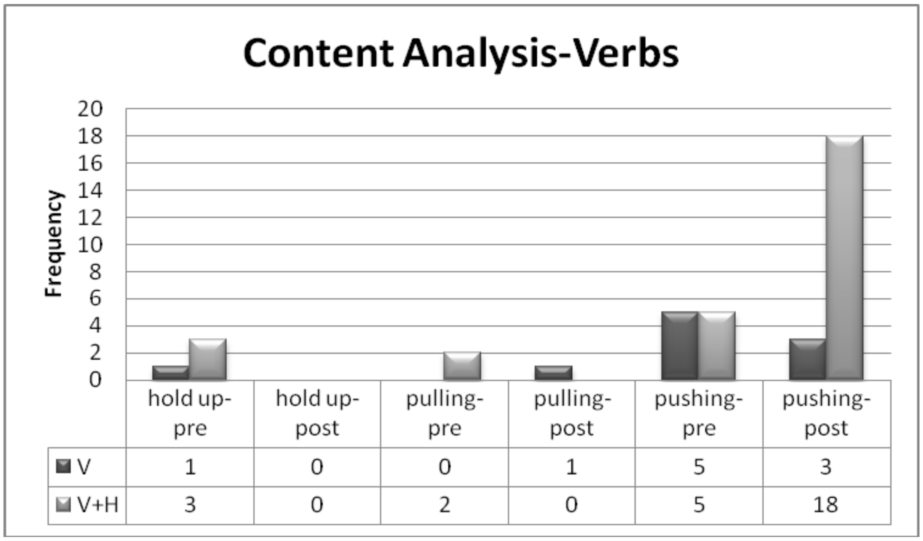
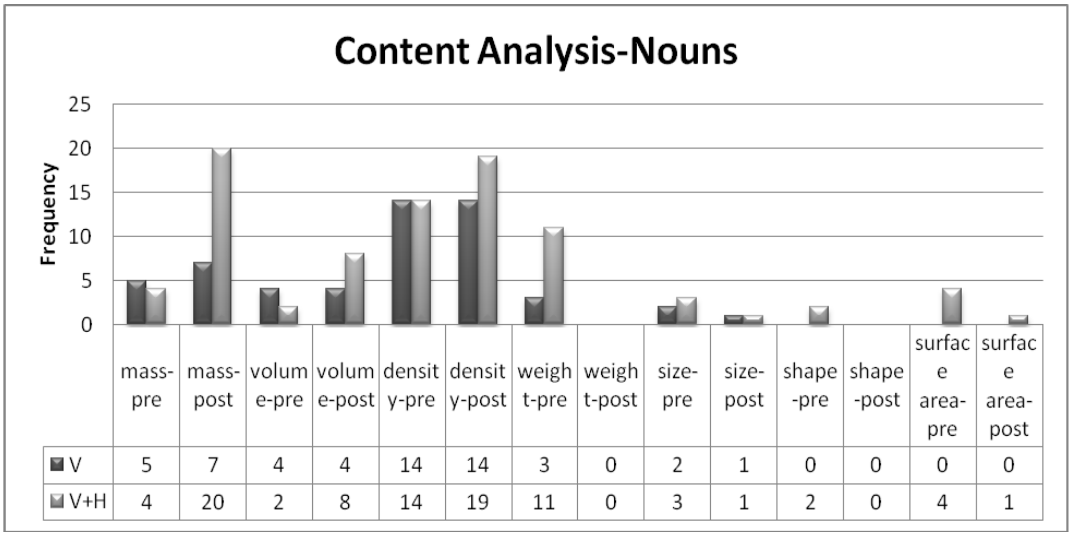


Figure 6. The summative content analysis of adjectives found in subjects' responses across treatment groups.



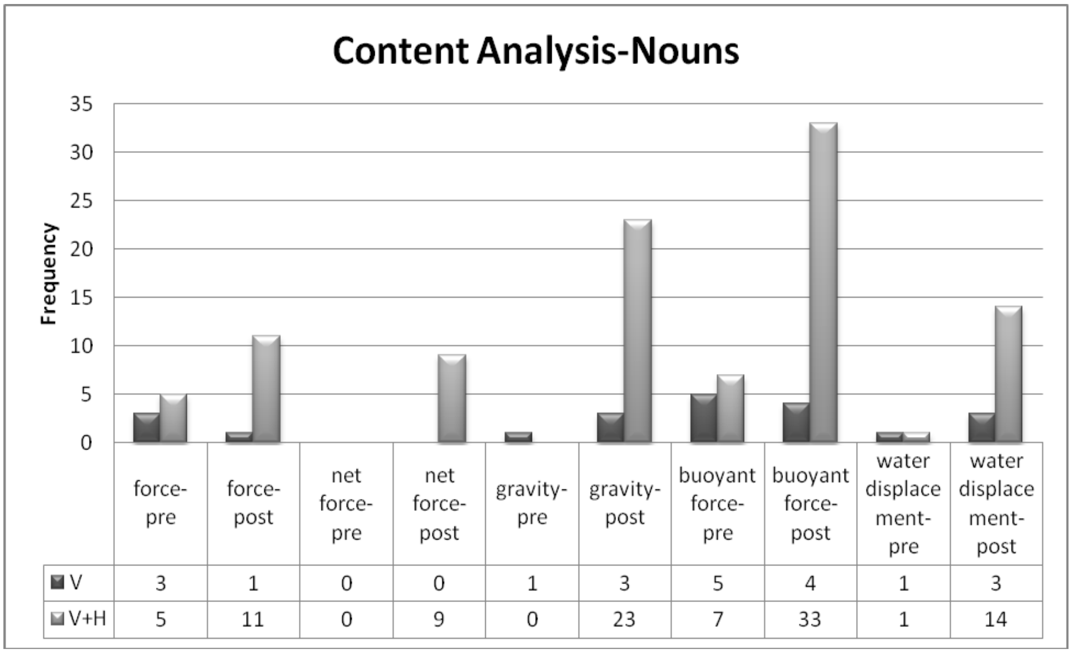
	hold up-pre	hold up-post	pulling-pre	pulling-post	pushing-pre	pushing-post
■ V	1	0	0	1	5	3
▨ V+H	3	0	2	0	5	18

Figure 7. The summative content analysis of verbs found in subjects' responses across treatment groups.



	mass-pre	mass-post	volume-pre	volume-post	density-pre	density-post	weight-pre	weight-post	size-pre	size-post	shape-pre	shape-post	surface area-pre	surface area-post
■ V	5	7	4	4	14	14	3	0	2	1	0	0	0	0
▨ V+H	4	20	2	8	14	19	11	0	3	1	2	0	4	1

Figure 8. The summative content analysis of 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

Figure 9. The summative content analysis of nouns found in subjects' responses across treatment groups.

Figures 8 and 9 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).

Discussion and Implications

Heywood and Parker (2001) suggested that students rarely think of floating and sinking as forces in action. Here we present preliminary evidence that adding haptic feedback (simulated touch) to a simulation for learning changes this. Through summative content analysis we demonstrated clear differences in the posttest explanations of Why Things Sing and Float (WTSF) across treatment groups. Learners that experienced the haptic feedback made more frequent use of terms like force, net force, gravity, buoyant force, and pushing. Subjects that had access to the haptic feedback also seemed more able to integrate the idea of water displacement and the critical role that water displacement plays in sinking and floating.

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, & select information for further processing. Such findings may lead to a novel theory of language mediated haptic cognition. A theory that builds on the idea of semiotic schemas (Roy, 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 & "top-down" action on the physical environment individuals are able to build conceptions of complex events, objects, and object properties.

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.

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) drawn from a single program at just one institution. Cleary this hampers the generalizability of this work. We also found that the WTSF rubric was not sensitive enough to accurately catalogue the responses of the study's sample. Designed for 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). Additional scoring issues were encountered with the concept mapping task. Here the trouble was not with the scoring scheme itself but rather with its application. The concept maps proved difficult to score with an interrater reliability of only 68%.

Ideas for future work born out of this initial study center on continuing to gather evidence of our theory of *Language Mediated Haptic Cognition* in other contexts. This includes the testing of this haptically-enhanced simulation for learning with other populations, of particular interest is upper elementary students. It might also be interesting and informative to assess students' understandings of forces, perhaps using the established *Force Concept Inventory* (Hestenes, Wells, & Swackhamer, 1992).

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