Investigating the Influence of Haptic Technology on Upper Elementary Students' Reasoning about Sinking & Floating

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Introduction

Current haptic technology enables the augmentation of computer-generated images with a simulated sense of touch. Some work contends that haptic feedback engenders experiential or embodied knowledge (Han & Black, 2011; Minogue et al., 2006; Minogue & Jones, 2009; Reiner, 1999; Williams, Chen, & Seaton, 2003; Wiebe et al., 2009; Young, et al., 2011) that would otherwise lie untapped. These affordances become important when one considers the invisible aspects that undergird many school science concepts (e.g. buoyancy, intermolecular forces, and magnetism) that students are expected to understand. **A**dvancing **S**cience **P**erformance with **E**merging **C**omputer **T**echnologies (ASPECT) combats "reasoning thin" elementary science curricula by building and pilot testing simulations for learning, incorporating both visuals and haptic augmentation that provide "conceptual encounters" with the invisible aspects of core science content; previously unseen and untouched aspects that lie at the heart of the scientific explanations.

Problem Being Addressed

ASPECT strategically addresses the need for well-designed and engaging conceptual encounters (Shepardson & Britsch, 2006) with the *invisible aspects* of science content at the elementary school level, a critical educational need. Many elementary school teachers assume that their pupils only function at the level of "concrete thinkers," limiting students' opportunities to practice complex reasoning about invisible phenomena. All too often, abstractions (ideas not tied directly to the concrete and directly observable) are thought to be beyond the students' grasp and in practice such mental activity is postponed until higher grade levels (Metz, 1995). The end result is often "reasoning thin" (Duschl, 2008) elementary science curricula that tend to overemphasize the concrete and overlook the more abstract "invisible" that undergirds a deep understanding of the content.

The ASPECT project combats this situation head on by leveraging haptic technology (simulated touch) to reach beyond what is typically practiced in today's classrooms to provide learners unparalleled access to "forces," a *foundational percept* (the basic component in the formation of concepts) of the physical sciences. Our first simulation in a planned series targeted buoyancy and used the Novint Falcon®, a force-feedback device (Figure 1), to help students reason about the gravitational and buoyant forces involved in sinking and floating. The Falcon is a point-probe haptic interface that is able to track 3 degrees of freedom (DOF) (x, y, and z coordinates) and provides 3-DOF force feedback (our simulation only used 2-DOF input and force-feedback to simplify the experience).

Figure 1. The Novint Falcon®.

Theoretical Framework

The study's framework is built using two main areas: what we know about students' thinking about buoyancy and grounded cognition. We look at each briefly in turn.

Buoyancy. Despite a lifetime full of everyday experiences, a scientifically sound explanation of buoyancy is difficult to construct. 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 suggest that novices 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 phenomena (e.g. Ginns & Watters, 1995; Halford, Brown, & Thompson, 1986; Hardy, Jonen, Möller, & Stern, 2006; Kohn, 1993). Understanding and explaining the sinking and floating phenomena also asks leaners to consider opposing forces; some earlier work describes the common conceptual difficulties that lie here (e.g. Driver, Rushworth, & Wood-Robinson, 1994; Heywood & Parker, 2001).

Haptically grounded cognition. This exploratory work builds on the recent study by Han &Black (2011) and hones in on embodied cognition as a way to isolate and describe the influences of haptic feedback. Embodied cognition, a relatively new approach to examining human cognition, emphasizes the importance of perception on conceptual learning. While more traditional theories of cognition suggest that knowledge is a network of abstract propositions stored in long-term memory in a format of semantic memory systems that are separated from our perception, bodily action and mental states, a growing number of researchers (Barsalou, 2008; Barsalou et al., 2003; Gibbs, 2005; Glenberg, 1997; Lakoff & Johnson, 1999) have asserted that thought and knowledge emerge from dynamic interactions between the body and the physical world. 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 can actually be drawn from multiple sources, including perceptual simulations and situated action (Han & Black, 2011). This framework suggests that multimodal mental representations created by physical interactions serve as a *cognitive grounding* for understanding abstract science concepts.

Procedure

Project Goals

ASPECT is a 3-year *Exploratory Project* targeting the *Learning Strand* of the National Science Foundation's DR K-12. The specific project goals are to:

- Successfully integrate the Unity™ game engine and haptics as an innovative teaching tool.
- Design and build a series (3) of prototype science simulations targeting the core science content of forces and interactions and matter and its interactions.
- Clarify the construct of *haptically-grounded cognition* in an attempt to isolate and describe the differential impact of the haptic augmentation of science simulations.
- Conduct small-scale pilot tests to provide proof-of-concept and preliminary estimates of impact of haptically-enhanced simulations for learning upper elementary (grade 3-5) science content.

Hypothesis and Research Question

The core research question that underpins our exploratory project is: *How does the addition of haptic feedback influence users' understandings of core, often invisible, science content?* Our working hypothesis is that integrating the simulated sense of touch (haptic force feedback) along with visual information impacts the way in which learners perceive, attend to, and select information for further processing and that 'haptic grounding' facilitates the formation of concepts that are fundamentally different than ones formed form visual information alone.

Our Approach

ASPECT's development cycle includes focus groups (both children and expert STEM teacher informants that provide the core team with feedback on beta versions of our simulations), usability testing (that generates data regarding task performance, user behavior, and user preference), and small-scale classroom pilot testing.

Year 1 Focus Groups. Our STEM Teacher Focus Group helped us further clarify and operationalize our instructional intents and reinforced the practical importance of incorporating in-game scaffolding tools like a virtual notebook to be used as a planning and reflective tool. The teachers also provided valuable insights into the language demands of our assessments and supported our varied approach (open-ended prompts, close-ended questions, and interviews) to the assessment of the simulations.

During the Student Focus Group session we engaged 5th grade students (*N*=12) in a series of physical experiments around sinking and floating to better understand their current conceptual status here. *Why Things Sink and Float* (WTSF) prompts (Kennedy & Wilson, 2007) were given before and after the experiences (Figure 2).

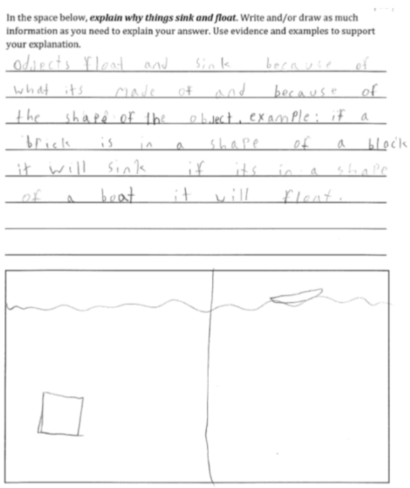

Figure 2. The WTSF prompt (Kennedy & Wilson, 2007).

Figure 3. Students engaged in focus group activities.

Results of this focus group session suggested that students had a lot of difficulty working with the physical materials (e.g. shaping the clay), underscoring the value of virtualizing these experiences. Students also seemed stuck (conceptually) at the "***heavy things sink and light things float***" level. Only a few students were able to consider the role of water displacement in sinking and floating even with direct prompting. In the end, work with students early on helped us zero in on our instructional goals: sinking and floating depends on more than just the object's mass; one also needs to consider the shape and density of the object, asan object will float if it displaces a volume of liquid that has a mass equal to or greater than the mass of the object itself. Figure 3 shows some of this work.

Usability testing. During the later Usability Testing these same students reacted to some artwork and character options, tried out a concept-mapping task, and used an early version of the sinking and floating simulation. At this point the simulation had evolved into what was essentially a series of virtual experiments that targeted two key dimensions of sinking/floating, an object's size, shape, and the material itself (density). The usability testing suggested that we had built a stable simulation that was engaging to the students and also helped us refine our assessment approaches.

From this point on we refined our simulation, splitting it into distinct scenes, adding directive text boxes, and in-simulation prompts/notebook interface. Students explored virtual blocks of familiar materials (cork, wood, brick, and steel) in a series of four scenes (Figure 4). Users progressed through the scenes in succession and could not go back. Each scene was designed to help students isolate a contributing factor to the sinking/floating phenomenon as shown below:

- Scene 1: Four objects, same size, different material.
- Scene 2: Four objects, different size, same weight.
- Scene 3: Two materials with two sizes.
- Scene 4: Two materials with multiple different shapes

Figure 4. Representative screenshots of our sinking and floating simulation.

Pilot testing. More formal pilot testing of the simulation involved a convenience sample of 47 (*N* = 27; 12 female, 15 male) and 5th (*N*= 20; 7 female, 13 male) 3rd grade students from a single local elementary school. A randomized pre-test-post-test control group research design was used. Two main groups were formed from this sample population, haptic feedback (*N* = 24) and no haptic feedback (*N* = 23). Both groups experienced the same core simulation (described above) and used identical interfaces. One group received bi-modal feedback (visual + haptic; H) and the other group did not (visual only; NH). All participants completed the *Why Things Sink and Float* assessment. Participants progressed through the simulation individually at their own pace. On-board data collection gathered start time, responses to in-simulation prompts, and end time. Post-simulation all participants completed the WTSF assessment again.

Users also completed a two-tiered assessment body diagramming task. Finally, we employed screen capture software (Fraps®) to obtain real-time recordings of users' interactions with the simulation. We have 28 recordings (58% of total users) and we discuss these data in the next section.

Analyses and Findings to Date

Paper-pencil Assessments

WTSF and our SOLO taxonomy. We scored participants' responses using a simulation-specific Structure of Observed Learning Outcomes (SOLO) taxonomy (Biggs, 1999; Biggs & Collis, 1982). Our taxonomy is in the Appendix. The consensus estimate of inter-rater reliability was 73% (a simple percent-agreement figure). Discrepancies were discussed in person and final SOLO taxonomy scores were assigned. Independent t-tests (alpha = .05) were conducted using the gain scores on the WTSF prompt.

Results. Third grade students with force feedback (H) showed an average of 2.92 on the posttest compared to 2.27 for the visual only (NH) group (mean gains of .846 and .636 respectively). The Cohen's d of 0.35 here points to a modest effect size of haptics for the 3rd graders in our sample. No significant differences across treatments were observed in the 5th graders from our study. Additionally, no significant gender differences in mean gain scores were found (female *M*= 0.60; male *M*= 0.84).

The results showed that regardless of their treatment group 3rd graders gained 0.75 points and 5th graders gained 0.95 points on our SOLO taxonomy, suggesting that many users moved beyond the incomplete notion that things sink or float because of weight alone to considering additional factors like the material and the shape of the object. We believe this provides some preliminary evidence of a move from *phenomenon-based reasoning* to *relation-based reasoning* (Driver et al., 1996). The recognition that multiple factors (mass, size, shape, material) must be considered when reasoning about buoyancy. This and the notion of an object being 'heavy for its size' presented themselves as candidates for stepping stone concepts (Wiser & Smith, 2009).

Delayed Posttests. Roughly four (4) months after pilot testing, a portion (N= 20; 74%; 10 H, 10 NH) of our 3rd grade sample completed the WTSF prompt again. Looking across treatment groups at the gain scores from the pretest and delayed posttest shows (H:*M*= 1.2 points; NH: *M*= 1.5 points) can be seen. Scores were stable for 7 students and no student had a negative gain score. When looking at the responses qualitatively, some interesting findings emerge. It seems that more haptic users called upon the notion of 'pressure' when explaining the sinking/floating phenomenon. Examples include: "too much PRESHOR"; "heavy and have a lot of pressure"; "water can't hold it up"; and "a lot of weight ON IT"(66.7% of all mentions received force-feedback).

Two-Tiered assessments. Descriptive results of the first two-tiered assessment indicate that on the free-body diagramming task (regardless of treatment group) 5 students (10%) didn't draw any arrows, 39 (81%) drew one arrow on each object (downward for the sunken block and upward under the floating block), and 4 students (8%) drew multiple arrows surrounding each of the blocks. Interestingly, not a single student in the study drew opposing forces in our free-body assessment and we have no evidence of students using opposing forces in their explanations. This finding is in line with earlier work describing conceptual difficulties (e.g. Driver, Rushworth, & Wood-Robinson, 1994; Heywood & Parker, 2001). On the near transfer task, 17 students (35%) answered correctly (that the combined block would float). Of these 17 users, 7 (41%) received haptic feedback and 10 (59%) had only visual feedback. We have not yet examined the second tier of this item.

Post-hoc content analysis. User's written responses to the WTSF prompt are currently being further analyzed using summative content analysis (Hsieh & Shannon, 2005). Based on some earlier unpublished work we did in this area, we are looking for and counting specific terms in manifest content. We think the use of these specific terms can serve as signals for the influence of haptic feedback; we call them 'haptically grounded' words. The terms include: Nouns: material, mass, volume, size, shape, density, force, gravity; Adjectives: heavy/light, more/less dense, air inside; Verbs: balance(d), push, pull, hold up. Looking at these data across conditions will help us untangle the influence of haptics and will feed the development of a novel theory of *language mediated haptic cognition*.

Fraps® Analysis.

Our Typology of User Interactions. We have 28 recordings (58% of total users); of these 11 have (23%) have been score by two researchers (percent agreement 88%). To analyze these we have developed a typology (see Appendix) of user behaviors captured by the FRAPS® screen recording software to help us better pinpoint any differences in user actions across the treatment groups (haptics vs. no haptics). It includes the observable behavior, a brief description of the behavior (pointing to its potential significance), and what we will look for with each behavior (our dimensions of interest). The first two actions in our typology (i.e. picking up objects and dropping objects) suggests a "try it and see what happens" approach to the simulation (Metz, 2011). Such phenomenon-based actions (Driver et al., 1996) are characterized by a focus on surface characteristics of phenomena. Epistemologically, these actions often lead to explanations that are re-descriptions of the observed phenomenon; explanation and description are not distinguished. We suggest that the latter three behaviors (i.e. stacking objects, pulling objects into the water, and holding/moving objects underwater) are signals of deeper engagement with the simulation. Epistemologically, these behaviors move beyond phenomenon-based action and reasoning to include user actions aimed at better understanding the relationships between/among variables/conditions. Here users may manipulate a variable identified by them as potentially influential on the phenomenon under investigation (e.g. dragging the object to different depths in the water) or explore the impact of additional (and perhaps unintended) conditions or situations (e.g. stacking the objects). Findings here are just emerging…

Contributions to Date

While we are still actively analyzing our Year 1 data we believe that we have already produced work that can impact the principal disciplines of science education and human-computer interactions (HCI), aside from the development of a Novint Falcon®-Unity game engine interface. We have findings about upper elementary students' learning about sinking and floating specifically and forces more generally. We feel that our sinking and floating simulation did move students towards a fuller understanding of the phenomena. That is, we present preliminary evidence that many students moved beyond the incomplete notion that things sink or float because of the weight alone to consider additional factors like the material itself and the shape of the object.

That being said, we were a bit surprised that there were not greater treatment effects evidenced in our pre-post analysis of the WTSF prompt. The impact of force feedback remains difficult to detect and we continue to examine our data (e.g. the remaining Fraps® recordings and a content analysis of the WTSF responses) for signals of a differential impact of haptics.

We were also struck by the fact that not a single student in the study (3rd; n = 28, 5th; n= 20) drew opposing forces in our free-body assessment. Images were virtually identical across the population depicting a downward arrow on the sunken block and an upward arrow on the floating block. Rarely were multiple forces shown acting on an object and we have no evidence of students using opposing forces in their explanations. This suggests (as others have) that students (at least in our study) do not reason about or with forces intuitively or easily.

We also believe that the analytic frameworks or taxonomies we have developed and are using can aid others working on related investigations. Three (3) usable taxonomies were created (an easily adaptable Simulation Specific SOLO, a phenomenon vs. relation-based reasoning tool for looking at real-time recordings of user actions, and a unique approach to content analyses built on the existence of haptically-grounded terms.)

From a human-computer interactions (HCI) perspective, we walked away from the pilot-testing realizing that users may not be fully capitalizing on the force feedback the haptic device affords them. We found that users in the haptic feedback treatment did not hold the objects in/under the water as we expected them to do intuitively. This inaction may have lessened to cognitive impact of being able to "feel the buoyant force". This sort of evidence lends credence to Klatzky, Lederman, and Matula's (1993) visual dominance model of haptic cognition where visual analysis is exhausted before any haptic exploration is initiated. Users also only felt the net force of the combinded object weight and buoyant force, which may have hindered the ability to reason about opposing forces.

Despite a voluminous literature base from the fields of developmental and cognitive psychology regarding underlying principles and processes of the haptic perception and cognition, very little is known about the true educational impact of haptic technology (Minogue & Jones, 2006). There is a critical need for research that systematically links the basic research on haptic cognition with the applied research on haptics as an intervention for change

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Appendix

ASPECT's Simulation Specific SOLO Taxonomy

Level	Score	General Description	Task/Context Specific Description	Sample Student Responses
Prestructural	1	The task is not attacked appropriately, the student hasn't understood the point, or question is reworded.	No aspect of buoyancy (sinking/floating) has been used in the response. Either the student does not understand the question or the student has answered with ideas/concepts that are ***unrelated/unproductive***.	*Things sink or float because of their air mass and inertia.* *Some things sink because the center mass will get angry if it is too far to the left or right.*
Unistructural	2	One aspect of the task is picked up and used.	A ***single useful aspect*** of sinking/floating is mentioned. Useful concepts include weight/mass, size, shape, material, & force.	*Things float when they have a little weight.* *Things sink because sometimes its to hevey or its gravity that pulls us down.* *I think why things sink is because the bottom of it is not straight.* *I think things sink or float because of shape not weight. That's why boat are not just a block.*
Multi-structural	3	Several (two or more) aspects of the task are learned but are treated separately.	***Two or more useful aspects*** have been mentioned ***but not integrated***. Useful concepts include weight/mass, size, shape, material and/or force.	*If it is big metle it will sink. If it is small metle it will sink…* *I think sink or float because of what they are made of & their shape.* *They sink or stay floating because there materials, mass, and shape.* *Things sink and float because of 3 thing matter, shape, and size without them we couldn't make things float or sink!*

Level	Score	General Description	Task/Context Specific Description	Sample Student Responses
Relational	4	The components are integrated into a coherent whole, with each part contributing to the overall meaning.	***Two or more useful aspects*** are included and together they contribute to an explanation of sinking/floating. The response ***attempts to explain how/why*** weight/mass, size, shape, and/or forces contribute to sinking/floating.	*Things sink/float due to weight, size, and shape. Heavy things can float if you change its shape.* *Objects float & sink because of what its made of and because of the shape of the object. If a brick is in the shape of a block it will sink. If it is in the shape of boat it will float.* *Doesn't matter how big it is. If there is a big block that barely weighs anything and a tiny block that is metal. The big block will float and the tiny one will sink. And when something is heavy and it sinks you can make it into a bowl and it will float.* *Objects float and sink because of what it is made of and because of the shape of the object. Example: if a brick is in a shape of a block it will sink if its in a shape of a boat it will float.* *I think it depends on mass and shape because on game the shapes were different sizes and they still were floating. The material were cork and wood but when the metal was in a bowl shape it floated.* *I think thinks sink and float because of their material, shape, size, and weight, Even though the material is made out of heavy things the shape and size can effect it.*

Level	Score	General Description	Task/Context Specific Description	Sample Student Responses
Extended Abstract	5	The integrated whole at the relational level is reconceptualized at a higher level of abstraction, which enables generalization to a new topic or area, or is turned reflexively on oneself .	Responses reflect applications/extensions beyond the immediate context. These include more abstract concepts such as density, volume, and/or water displacement.	

ASPECT's Typology of User Behavior-Sinking & Floating

Action Type	Observable Behavior	Description	Dimension(s) of Interest
Phenomenon-based	Picking Up Objects	At a minimum, all users picked up and put down some of the objects; our typology presupposes this. Haptic users could feel the weight/mass of objects.	object being picked up; frequency
	Dropping Objects	This behavior provides visual feedback for sinking and floating. Haptic users also felt the object being released.	frequency of drops; object being dropped; drop height; subsequent action
Relation-based	Stacking Objects	This behavior suggests a deeper level of engagement with the objects in the scenario. Haptic users that push and/or lift stacked objects could feel differences in the magnitude of the forces (gravitational and buoyant).	frequency; duration; objects being stacked; order of objects; stacked objects lifted; stacked objects pushed down; subsequent actions
	Pulling Objects into the Water	This behavior provides the haptic user with force feedback representing the gravitational and buoyant forces at the moment of submersion, providing a unique opportunity to consider these opposing forces. The user can also see the water level rise and fall, suggesting a relationship between water displacement and buoyant force.	frequency; duration; object being pulled; subsequent action
	Holding/moving Objects Underwater	This behavior provides the haptic user with force feedback representing the combined gravitational and buoyant forces on the object while submerged.	frequency; duration; object being submerged; subsequent action