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Haptic feedback and students' learning about levers: Unraveling the effect of simulated touch

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ABSTRACT

While there has been extensive experimental research on haptics, less has been conducted on cross-modal interactions between visual and haptic perception and even less still on cross-modal applications in instructional settings. This study looks at a simulation on the principles of levers using both visual and haptic feedback: one group received visual and haptic feedback while the other just visual feedback. Using the triangulation of learning scores, eye tracking data, and video analysis of interaction with the levers, the efficacy of haptic feedback to improve learning was explored. The results indicate that while the total fixation time on the levers and numeric readout was greater for the visual and haptic group, very similar patterns of visual attention were seen between groups. Perhaps surprisingly, the visual only group scored higher on an embedded assessment. Explanations for these results are synthesized from theories of cross-modal perception and cognitive architecture.

1. Introduction

Despite ever increasing interest in the creation and use of computer-based instructional programs (e.g. interactive simulations, virtual labs, digital learning environments) for the teaching of school science concepts (Hennessy et al., 2007), the extent to which these technologies impact students' understandings is still unclear. While numerous studies (e.g. Bransford, Brown, & Cocking, 2000; Doerr, 1997; Linn, 2003; Winn, 2002; Zacharia, 2003) point to potentially positive impacts, other work (e.g. Bayraktar, 2002; de Jong & van Joolingen, 1998; Hsu & Thomas, 2002; Steinberg, 2000) suggests a rather tenuous link between the use of these technologies and learning gains.

Proponents of computer-based simulations note that these virtual environments allow students to make comparisons between elements of a system and witness the outcomes much as you would with their physical counterparts (Linn, 2004). In addition, students may also be able to explore relationships in simulations not feasible in the physical realm because of limits of time, space, cost, or safety. It is likely that the efficacy of this experience will be determined in part by how effectively key information about the phenomena can be communicated to the student, mediated by the computer-based system. Improvements in computer-based graphics have meant that very rich, high-resolution color graphics can be communicated visually to the student through most computer systems. Similarly, improvement in audio technology now means that most auditory-based information can also be communicated at high fidelity. While these two modalities cover much of the sensory information instructional designers might want to communicate to learners, it does not cover the full sensory range of what could be communicated nor does it address the general limitations in how learners communicate back to the simulation environment.

Along these lines, evolving technologies now make it possible to extend students' interactions with these computer-based learning environments beyond the audio and visual realm to include haptic (i.e., simulated touch) feedback (Burdea, 1996; Kátai, Juhász, & Adorjáni, 2008; Revesz, 1950; Robles-De-La-Torre, 2006). Haptic feedback devices provide a whole new modality of experience that can be tied directly to user input devices, more tightly binding the user experience directly to the simulated environment. 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

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the hand and arm that gather sensory information as users "feel" and manipulate two and three-dimensional virtual objects and events (Jacobson, Kitchen & Golledge, 2002; Jones, Minogue, Tretter, Negishi, & Taylor, 2006; Minogue, & Jones, 2006).

With haptic devices, such as the one seen in Fig. 1, not only can the simulation communicate haptic information about the phenomenal response to the learner, but also provide a more robust feedback mechanism as the learner interacts with the system. This point-probe device 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 on the screen, simulating the sense of touch. While potentially a breakthrough technology for instructional simulation environments, there is a paucity of research to guide instructional designers. This paper will explore the efficacy of a haptically augmented simulation environment for use in middle school science education, capitalizing on eye tracking data to help unravel the influence of simulated touch on student cognition.

2. Impetus for the study

An appropriate area of science education to employ haptic interfaces may be simulations that require the learner to both apply and respond to force feedback from a system. In upper elementary and middle school science, the study of levers is a common topic where students typically interact with constructed lever systems via the direct application of force with their hands and similarly receive feedback through the same pathway. It would, therefore, seem logical that the inclusion of haptic feedback in a computer-based lever simulation would enhance its positive impact as a learning tool. But despite the surface logic of the positive benefits of this application of haptics technology in science education, existing research literature does not provide a clear answer to its efficacy.

2.1. Haptics in science education

Despite a voluminous and relatively robust literature base from the fields of developmental and cognitive psychology regarding underlying principles and processes of the haptic perception and cognition (e.g. Heller, 1991; Klatzky & Lederman, 2002; Loomis & Lederman, 1986) very little is actually known about the educational impact of haptic technology. This is due largely in part to the fact there are only a handful of studies (e.g., Florence, Gentaz, Pascale, & Sprenger-Charolles, 2004; Jones, Andre, Superfine, & Taylor, 2003; Jones et al., 2006; Minogue, & Jones, 2006; Reiner, 1999; Williams, Chen, & Seaton, 2003) that have examined the use of haptic interfaces within the context of teaching and learning science concepts. One such study examined the influence of haptic feedback on middle and high school students' concepts of small objects such as viruses (Jones et al., 2003). In this exploratory study, students used a *nanoManipulator* (which combines an atomic force microscope (AFM) with software, a desktop computer, and a haptic desktop device) and received tactile and kinesthetic feedback from 3-D AFM images of viruses. Using this interface, students were able to push, cut and poke an actual virus and feel the interaction between this virus and the probing tip of an AFM. The results of the study showed a positive affective impact in that students who received haptic feedback reported being more interested in and feeling as if they could participate more fully in the experience.

Building on this, additional work (Jones et al., 2006) was done to investigate the impact of different types of feedback devices (a sophisticated haptic desktop device, a haptic gaming joystick, and a mouse with no haptic feedback) combined with computer visualizations viruses and nanoscale science influenced middle and high school students' experiences. Results suggested that the addition of haptic feedback from the haptic-gaming joystick and the PHANToM (SensAble Technologies, n.d.) (Fig. 1) provided a more immersive learning environment that not only made the instruction more engaging but may also influence the way in which the students construct their understandings about abstract science concepts as evidenced by an increased number of spontaneously generated analogies that appeared during student discourse.

Reiner (1999) examined the role of tactile perception in the conceptual construction of forces and fields by employing a modified trackball that transferred a simulated force applied by a field to the learner's hand. Through the qualitative analysis of graduate student drawings she presented "embodied experiences" as a way to explain the positive educational impact of haptics. That is to say, this learning environment stirs up tacit embodied knowledge, previously unexploited non-propositional knowledge. This type of knowledge is in immediate (without the mediation of symbols and concepts) relation to objects and bodily acts. She goes on to suggest that haptic devices are interfaces that promote the use of bodily non-propositional knowledge in the building of more accurate mental models and representations.

Additionally, researchers have developed and pilot-tested a series of haptically augmented software programs for teaching elementary school students simple-machine concepts (Williams et al., 2003). Although the researchers noted that the findings of this study are not the

Fig. 1. The PHANToM® Omni ™ desktop device from SensAble Technologies, Inc.

result of rigorous statistical analysis, the work does accurately portray the positive opinions of the student users. Through post-experience surveys, students (second through sixth grade) from two elementary schools and an undergraduate Robotics/Haptics class reported that they felt the haptically-augmented projects were effective and provided suggestions for improvements to the software. (Williams et al., 2003). Work in this arena is still in its infancy and there exists a critical need for more systematic studies, set within the context of actual classrooms, so that we may better understand how students perceive, process, store, and make use of haptic information.

Part of the challenge of moving from traditional research on haptics to applied settings, such as instructional simulations, is that multiple perceptual modalities are invariably engaged. Work in the last decade has clearly indicated the deep connections between perception in different modalities for both endogenous and exogenous events (e.g. Driver & Spence, 1998; Lalanne & Lorenceau, 2004; Rorden, Green, Sasine, & Baylis, 2002). In this case, there is reason to believe that visual information about the lever will moderate how the haptic information is processed. In addition, the same attentional mechanisms that drive eye movement are also involved in the coordination and integration of visual and haptic sensory information. It follows that it is far easier to have visual and haptic attention to a common endogenous event (Driver & Spence, 1998). The issue at hand is what is the optimal combination of haptic and visual information for learning?

2.2. Leveraging eye tracking data

Where the haptic point-probe is acquiring information can be understood by tracking the location of the cursor on the computer screen. In this study, eye tracking methodologies are employed to understand where visual sensory information is being acquired and, by extension, derive insight as to how visual attention and perceptual processing is distributed across the interface. These methods provide a powerful tool to help determine what time was spent attending to what visual information, holding it in short term memory for possible integration into long term memory. If expected learning does not occur, and little or no time was spent attending to the visual information, then it points to a failure to guide the learner's attention to this information. If expected learning does not occur and adequate time was spent looking at the visual information, then this points to processing difficulties after the information is acquired in short term memory. Eye tracking can provide crucial information to help differentiate between these two scenarios (Wiebe & Annetta, 2008). Eye tracking can help explain why (or why not) learning has occurred by revealing strategies of multimodal information acquisition and the effects of cognitive load during this process.

Two key terms used when discussing eye movement are *fixations* and *gaze*. Fixations occur when the fovea, the area of the retina with the highest visual acuity, is stabilized over an object of interest (Duchowski, 2003). Research indicates that the gaze will tend to gravitate on areas that are salient, surprising, interesting, or important through experience (Henderson, 1992). Gaze simply refers to the total amount of time, fixative and non-fixative, that the eyes orient to in a particular region. Research has shown linkage between eye fixation behavior (locus, duration, and sequence) and a cognitive processing model for both graphic and textual visual materials (Just & Carpenter, 1976). That is, fixations are sensitive to the structure of the internal representation being constructed or operated on (Yarbus, 1967). For that reason, the pattern of eye movements is not random and people tend to fixate areas of the scene that are judged as "informative."

2.3. Combining haptics and eye tracking

The theoretical frame guiding the joint interpretation of visual and haptic data can be summarized in a few brief points. First, visual and haptic sensory information is mentally merged into a common, unified perception of a scene (Driver & Spence, 1998). Next, top down processing of sensory information and past experience makes real-time judgments of the richness and reliability of the information being received from different modalities and attenuates the weighting given to each source accordingly (Klatzky & Lederman, 1993; Lalanne & Lorenceau, 2004). Similarly, prior and ongoing experience will guide further acquisition of information. Finally, processing sensory information for learning has a cognitive cost—though not necessarily in a simple additive way—across multiple modalities (Sweller, Merrienboer, & Paas, 1998; Wickens, 2002).

With this in mind, the aim of the present study is to systematically explore students' learning about the three classes of levers via a haptically augmented virtual lab. The research questions include: At the time of use, how does the haptic interface alter the way learners interact with the virtual lab? At a more primary sensory level, how does the haptic interface alter the distribution of visual attention (since the visual modality is still the primary means of conveying information in this virtual lab)? And, as an outcome, how does haptic force feedback alter the development of conceptual understanding of levers? For that reason, learning measures, eye tracking data, and coding of system interaction behaviors with the haptic point-probe are all used in this study to better understand the impact of the haptics augmented virtual lab on conceptual learning.

3. Method

3.1. The instructional program

For this study, a computer-based virtual lab was developed and tested with middle school (ages 11–14) students attending a week-long science summer camp offered at a middle school by the university. The participants were from three different school systems that served rural, urban, and suburban students. The interactive program introduced participants to first, second, and third class levers and allowed students to create a lever by manipulating the fulcrum location, beam length, and amount of load placed on a lever. Each participant was exposed to three blocks of five trials; each block testing one type of lever. The maintenance of eye tracker system calibration was visually verified in between each of the three blocks of trials.

Within each trial, five screens (e.g., *Move Fulcrum, Apply Weights, Choose, Explore,* and *Answer*) were sequentially viewed by each participant. Students were allowed to self-advance to the each screen without time constraints. Students in the *Move Fulcrum* screen created their own lever by placing the fulcrum anywhere along the provided beam and in the *Apply Weights* screen, any number of 8 weights (each with equal masses) could be placed on the beam. In the *Choose* screen, the program generated a second lever that varied comparatively in terms of the number of weights applied, the fulcrum positioning or both. In this screen the student was asked to choose which lever required more force to lift the weights. After making the selection, the *Explore* screen allows the student to push the cursor pointer on the beam at a point of choice to "feel" the necessary force required to lift the weights (Fig. 2). This screen also had a numeric readout in the upper right quadrant of the screen that displayed numerically the force being applied to the lever. In the Uni-Modal group, students did not "feel" the force but were still provided all input functions and visual feedback that the experimental group was afforded. The *Answer* screen provided trial-specific performance feedback but not cumulative trial performance feedback. At the end of the computer program, students were given cumulative performance feedback, called the *embedded assessment*. Average engagement time with the virtual lab was 35 min. Finally, they were then provided a paper-based post-test and debriefed.

3.2. Study design

The study employed a randomized pretest-posttest control group design. All of the students ($n = 33$) used a PHANToM® Omni ™ desktop device (SensAble Technologies, n.d.) (Fig. 1) to navigate through the instructional program and to interact with the levers. Additionally, all students were given a visual numeric readout of the force being applied to the levers. However, students in the experimental group ($n = 20$) received bi-modal (Visual + Haptic) feedback as they completed the program. Conversely, members of the control group ($n = 13$) only received uni-modal (Visual Only) information as they worked with the levers, as a software switch allowed for the force feedback to be turned off. In this mode, the PHANToM behaved more like a computer mouse would.

Sensable Technologies' OpenHaptics™ toolkit was used for the rendering of the haptic feedback. While the PHANToM® Omni ™ is able to track the x, y, and z Cartesian coordinates, as well as the pitch, roll, and yaw of the virtual point-probe as it moves about a 3D workspace; in this particular application the device's tip motion was only mapped in the x–y coordinate plane. Additionally, the contact location with the lever was also fixed in the x–y coordinate plane. Students were able to make contact and push at any point along the lever. The displayed forces, whose magnitude ranged from 0.08 to 0.16 Newtons/cm^2, were in the y coordinate plane alone.

A subset of these students ($n = 17$; 9 receiving bi-modal and 8 receiving uni-modal feedback) had eye tracking data used for further analysis. Suitability of subjects for eye tracking (e.g., not on prescription medications that would dilate the pupils) and initial reliability analysis of the eye tracking data accounts for the reduced sample size. Prior to use of the virtual lab, all of the students took a pretest assessing their understandings of levers (described below). Immediately following the use of the virtual lab, students took a posttest. In addition, there was an embedded assessment within the program of the number of correct lever selections.

3.3. Data sources

Data regarding students' understandings of levers was generated using a 13-item written pre and posttest. Test items included ones aimed at assessing lower level declarative knowledge (e.g. name the class of lever pictured), as well as higher order conceptual

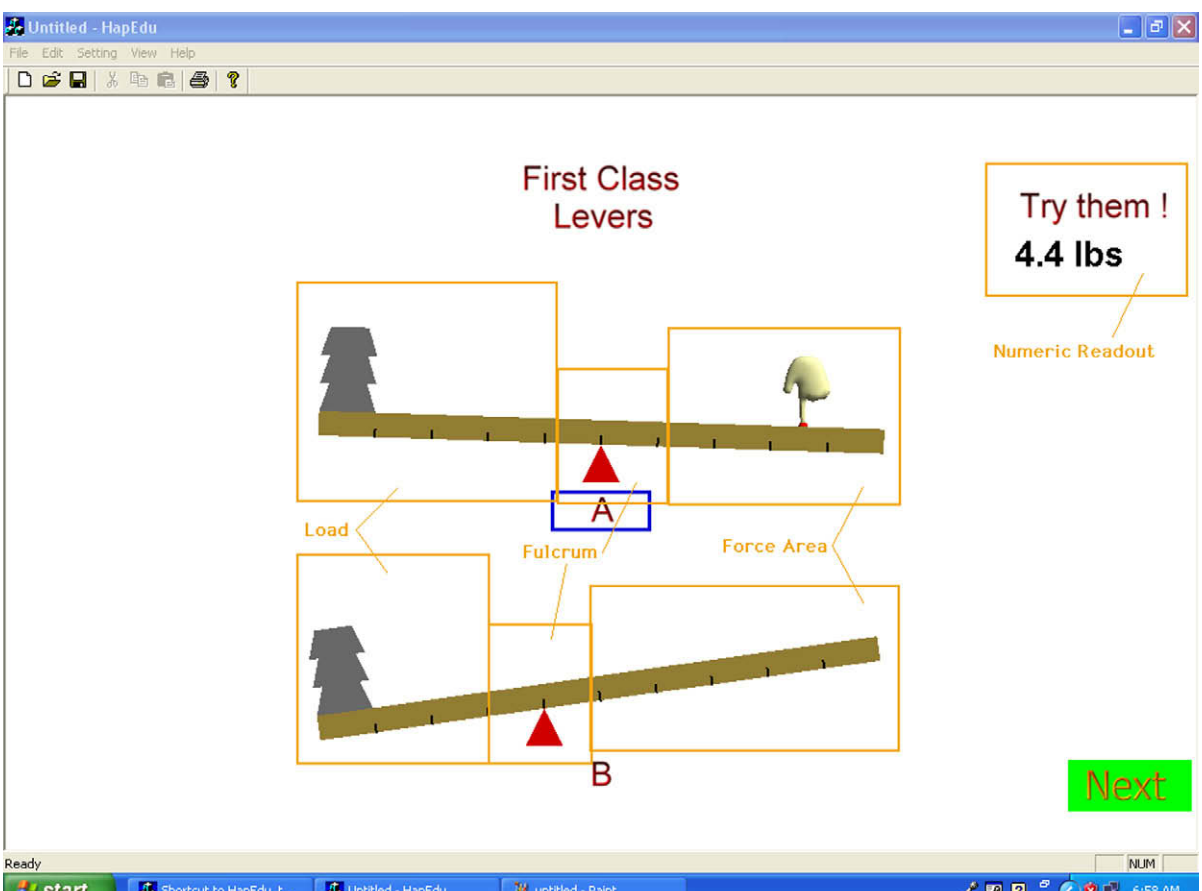

Fig. 2. The virtual lever lab on the *Explore* screen where students interact with the levers using the haptic device. The look zones used for analysis are represented in orange (but are not seen by the participant).

understanding of lever structure and function. Sample items are included in the Appendix. Additionally, the accuracy of students' responses to the 15 embedded tasks outlined above was recorded electronically.

A combined pupil and corneal reflection eye tracker was used to measure the gaze of the eye and the number of fixations occurring within defined look zones. These look zones were portions of the two levers and the numeric force readout seen in Fig. 2. In this study, a fixation was defined as lasting at least 100 ms—a threshold appropriate for an interface containing both text and graphic elements.

Finally, a video capture of the computer monitor of the complete virtual lab session was recorded. Video was analyzed for the number of times and location on the lever that the point-probe was applied to push down each lever. An "attempt" was quantified as each unique occasion that the virtual finger tip touched down on a lever and moved it. There was no time limit as to how long an attempt could take and it was not counted as a new attempt unless the finger tip came off the beam and moved as least 1cm away from the touchdown point on the beam.

4. Results

Written test data, eye tracking, and lever push data were triangulated to provide a better understanding of how haptic feedback influenced learning outcomes and what role changes in visual attentional distribution across the key information sources in the virtual lab may have had in these learning outcomes.

4.1. Knowledge assessments

Students' written pretest and posttest responses were scored and gain scores were calculated to allow for comparison across treatment groups (Table 1). Additionally, student scores on the embedded assessment tasks were tabulated and total scores were compared across the groups (Table 2). Given the small sample sizes and non-normality of the data, in both cases Mann-Whitney U tests were used to test for differences. Although no statistically significant differences were found on any of the pretest-posttest item comparisons, student scores on the embedded assessments varied significantly across the groups with students in the Visual Only group outperforming the Visual + Haptic students, as described in Table 2.

4.2. Look zone data

For the eye tracking data analysis, look zones were defined around the key elements of the first class levers (e.g., fulcrum, load, force location, numeric readout area). This was done for two key screens: where the students chose which of the two levers would take more force to move the load (called the *Chose* screen) and where the students explored the levers with the haptic device (called the *Explore* screen). These two screens were analyzed for three of the first class lever trials: one where the load was varied, one where the fulcrum location was varied, and one where both were varied. The primary interest in this analysis was the total amount of fixation time spent on the key elements of the lever and on the numeric readout seen on the *Explore* screen. This data was analyzed using Mann-Whitney U tests between the two groups.

4.3. Sequential analysis of visual attention

Table 3 shows the results of the total fixation time spent on the lever components on the *Explore* screen. There was a significantly higher total fixation time on the key screen elements for the Visual + Haptic group than the Visual Only group. The mean fixation time for the Visual + Haptic group was close to twice that of the Visual Only group. To see if this trend was the result of students spending significantly more time on the beam end where the point-probe cursor pressed down on the beam, an analysis was done of fixation time on just the beam end. While no significant differences were found, the trend again was for more fixation time for the Visual + Haptic group. Similarly, an analysis was done on the fixation time on the numeric readout area. No significant differences or obvious trends were seen. In addition, no significant differences in fixation time were seen on the *Choose* screen between the two groups.

To further explore the distribution of visual attention across the levers and numeric readout area on the *Explore* screen, a sequential analysis was undertaken (Gottman & Roy, 1990). This sequential analysis was based on a first-order Markov model, looking at the

Table 1
Comparison of lever knowledge gain scores across treatment groups.

	Visual + Haptic (n = 20)				Visual Only (n = 13)					
	M	*SD*	Mean rank	Sum of ranks	*M*	*SD*	Mean rank	Sum of ranks	*U*	*p*
Item 1	−0.09	0.42	18.98	436.50	0.12	0.60	22.56	383.50	160.50	.206
Item 2	0.35	0.71	21.54	495.50	0.24	0.56	19.09	324.50	171.50	.466
Item 3	0.22	0.80	19.78	455.00	0.35	0.70	21.47	365.00	179.00	.625
Item 4	0.30	0.47	20.28	466.50	0.29	0.69	20.79	353.50	190.50	.874
Item 5	−0.09	0.51	19.85	456.50	0.00	0.50	21.38	363.50	180.50	.588
Item 6	0.26	0.62	19.72	453.50	0.35	0.70	21.56	366.50	177.50	.584
Item 7	0.35	0.57	22.59	519.50	0.00	0.79	17.68	300.50	147.50	.149
Item 8	0.17	0.58	20.98	482.50	0.12	0.49	19.85	337.50	184.50	.708
Item 9	0.09	0.67	22.63	520.50	−0.24	0.66	17.62	299.50	146.50	.136
Item 10	0.48	0.51	21.83	502.00	0.29	0.59	18.71	318.00	165.00	.338
Item 11	0.13	0.63	18.93	435.50	0.35	0.60	22.62	384.50	159.50	.263
Item 12	−0.09	0.67	20.26	466.00	−0.06	0.56	20.82	354.00	190.00	.861
Item 13	0.09	0.60	19.07	438.50	0.29	0.47	22.44	381.50	162.50	.272

Note: Items were scored dichotomously 1 (correct) to 0 (incorrect).

Table 2
Comparison of embedded assessment score across treatment groups.

	Visual + haptic ($n = 20$)				Visual only ($n = 13$)					
	M	*SD*	Mean rank	Sum of ranks	*M*	*SD*	Mean rank	Sum of ranks	*U*	*p*
Total embedded assessment score	11.85	1.18	12.28	245.50	13.54	.88	24.27	315.50	35.50	.000*

Note: Possible scores were from 0 (low) to 15 (high).
* $p < .05$.

Table 3
Comparison of total fixation time (seconds) on first class levers during the explore screen.

	Visual only ($n = 8$)				Visual + haptic ($n = 9$)					
	M	*SD*	Mean rank	Sum of ranks	*M*	*SD*	Mean rank	Sum of ranks	X^2	*p*
Total fixation time	5.53	4.07	6.37	51.0	10.09	4.88	11.33	102.0	15.50	.048*

* $p < .05$.

conditional probabilities of gaze movement between the previously mentioned look zones; that is, whether the movement of gaze between any pair of zones happened more often than might be expected by chance. This analysis was undertaken by first looking at the likelihood ratio chi-squared test (G^2) of the overall log-linear model of all transitions between zones on the lever and numeric readout area (Table 4). Repeat fixations in the same zone were not counted in this model. The significant chi-squared test indicated that one or more transitions between zones happened more often than would be expected by chance.

Because transitions were occurring in a non-random fashion, the overall model analysis was followed by an examination of the z-score residuals for specific transitions between zones. Those transitions with the largest absolute values indicate transitions that happened considerably more or less often than would be predicted and, therefore, are the likely be the cause of the significant chi-squared test. Table 5 shows the ten largest residual transitions for each condition. Zones were ordered in each row in the table as occurring first (lag0) or second (lag1) in the pair sequence of zones. First item of note is the overall smaller residual values for the Visual Only group compared to the Visual + Haptic group, mirroring the Visual group's smaller G^2 value.

The Visual Only group did show some trends of interest, including that the movement to and from the Beam A end where force was applied to the numeric readout area was seen more often than expected. In addition there was movement to the Beam B fulcrum from the Beam B end and from outside the beam area more often than expected. Movement between the beam end and fulcrum of the opposing lever is seen much less than expected, as reflected in four of the five negative residuals.

For the Visual + Haptic group, a similarly strong trend of movement to and from the Beam A end where force was applied, to the numeric readout area more often than expected. However these movements were happening at frequencies two to three times larger than seen in the Visual Only group. There was also larger than expected movement from the Beam B end to the numeric readout. As with the Visual Only group, there was larger than expected movement between the Beam B end and fulcrum. Movement between the two beam ends and the fulcrum and opposing beam end are seen much less often than expected.

The same participants engaged in the same three trials that were analyzed for eye tracking were analyzed for lever push attempts and averaged. Again, the Mann-Whitney U test was used to compare the two groups. The Visual + Haptic group attempted significantly more pushes than the Visual only group though both groups only made slightly more than one attempt, on average, per lever (Table 6).

5. Discussion

The results are both interesting and somewhat surprising but should be viewed cautiously until further studies can replicate these results. Since learning about the principles of levers requires students to understand the relationship between the spatial location of the load, fulcrum, and force along with the relationship between the amount of load and the amount of force needed to move it, visual attention to and integration between these elements will be important. The eye tracking data indicates that the inclusion of haptic feedback significantly increased the amount of time spent fixating on these key elements relative to other portions of the computer interface. This is reinforced by the finding that this significant difference between treatments only occurred on the *Explore* screen, where students were interacting with the levers using the haptic point probe, and not on the *Choose* screen where they were simply using visual information to choose which lever would take more force to move the load. However, while more fixation time was spent on the levers and numeric readout in the Visual + Haptic condition during the *Explore* screen, it did not create large changes in the pattern of movement between key elements on the screen, nor did it lead to better performance on the embedded assessment. On the contrary, the Visual Only group performed better on the embedded assessment.

Table 4
Likelihood ratio chi-squared test for the overall log-linear model of transitions between zones.

Visual only ($n = 8$)			Visual + Haptic ($n = 9$)		
df	G^2	*p*	*df*	G^2	*p*
41	125.87	.0000*	41	225.79	.0000*

* $p < .05$.

Table 5
Ten largest transition z-score residuals for each condition.

lag0	lag1	Observed Freq	Observed Error	Expected Freq	Expected Error	Residual
Visual only						
s	ba	30	5.23	19.51	2.91	10.49
ba	s	28	5.07	19.06	2.87	8.94
bb	fb	16	3.90	7.40	1.42	8.60
x	fb	11	3.26	4.68	1.02	6.32
bb	ba	8	2.79	13.04	2.20	−5.04
s	x	3	1.72	8.07	1.58	−5.07
bb	fa	2	1.41	7.16	1.40	−5.16
fb	ba	6	2.43	11.18	1.98	−5.18
ba	fb	6	2.43	11.63	2.03	−5.63
fa	bb	2	1.41	8.01	1.50	−6.01
Visual + Haptic						
s	ba	84	8.63	63.74	5.72	20.26
ba	s	78	8.35	59.91	5.51	18.09
fb	bb	28	5.19	12.28	1.71	15.72
bb	s	50	6.83	37.97	4.11	12.03
bb	fb	23	4.72	11.53	1.63	11.47
ba	fa	34	5.70	23.21	2.79	10.79
ba	bb	16	3.96	27.57	3.14	−11.57
fb	s	13	3.57	26.69	3.29	−13.70
bb	ba	12	3.44	26.14	3.04	−14.14
s	fb	13	3.57	28.11	3.42	−15.11

Glossary
ba, Beam end (right of fulcrum), Lever A.
bb, Beam end (right of fulcrum, Lever B.
fa, Fulcrum, Lever A.
fb, Fulcrum, Lever B.
wa, Weights, Lever A.
wb, Weights, Lever B.
s, Numeric Readout.
x, Any other area on the screen.

Table 6
Comparison of lever push attempt averages across treatment groups.

	Visual only ($n = 8$)				Visual + haptic ($n = 9$)					
	M	*SD*	Mean rank	Sum of ranks	*M*	*SD*	Mean rank	Sum of ranks	*U*	*p*
Lever push attempts	1.02	.11	6.38	51.00	1.35	.09	11.33	102.00	15.00	.038*

* $p < .05$.

5.1. Modality effects

While the haptic feedback afforded the student force feedback information, both groups showed the same patterns of movement to and from the beam end and the numeric readout. This was an interesting finding, as it could have been conjectured that since the haptic feedback provided force information via this modality, visual confirmation of numeric value of the force was not needed, especially since the task only required the student to estimate which lever took more force (not an absolute value of the amount). This observed difference is parsimonious with past research that indicates that haptic information will not necessarily dominate over visual information, especially when visual information is perceived to be as useful or more so (Driver & Spence, 1998; Klatzky & Lederman, 2002). That is, "modality specificity in perceptual encoding" (Klatzky & Lederman, 1993, 2002) may have influenced students' interactions with the instructional program and ultimately what was learned. This notion, described as the differential appropriateness of visual and haptic information, suggests that when vision is available and adequate for a task, haptic exploration may not be evoked due to its relatively high processing cost. In this case, the visual information contained in the numeric readout may have been preferred over utilizing the haptic feedback information. Additionally, the visual recognition of an object and processes may rapidly trigger the retrieval of information about properties and events stored in memory that are semantically accessible; thus eliminating the need for direct perceptual encoding by vision or haptic exploration.

The analysis of the push attempts is in line with the larger overall fixation time for the Visual + Haptic group. The results indicate that haptic feedback may have induced students to spend slightly more time interacting with the levers. The results of this study, however, leaves it inconclusive as to how these differences in fixation time between the groups might have impacted cognitive integration of the lever components.

An interesting result was considerably more movements between the beam end and numeric readout in the Visual + Haptic condition. Not only were there considerably more moves between Beam A end and the numeric readout for Visual + Haptic, but only the Visual + Haptic group showed a similar trend for moves between Beam A end and the numeric readout. These results support the notion that the haptic feedback did not reduce the perceived importance of the visual readout of the numeric display for the Visual + Haptic group.

5.2. Impact on learning?

Ultimately, what matters is how haptic feedback influenced conceptual understanding about levers. While the eye tracking and video analysis point to increased attention on the crucial elements in the *Explore* screen for the Visual + Haptics group, this did not seem to translate into better understanding of levers. With the embedded assessment, the Visual Only group performed better while the more comprehensive written pre-post assessment showed no difference. While the choice of levers that the assessment is based on takes place in the *Choose* screen, the hope was that the haptic feedback on the next screen would provide a sensorially rich point of reflection on their choice that would lead to better performance on future lever trials. Plausible explanations for the observed results revolve around the complex interplay of issues regarding assessment, cognitive architecture, and perception.

With regards to assessment, it may be that there was a mismatch between a "sensorially rich" instructional program and the written paper and pencil pre and post assessment items used. On the other hand, the embedded assessment more directly reflected the interaction the students were having with the levers. Here, however, the haptic interface seems not to have contributed to learning.

In discussing the results, attention must be given to the cognitive architecture (Baddeley, 1992; Sweller, 1988; Sweller et al., 1998) of the user and the limitations of the cognitive system in the processing of new information. While the haptic interface may have affected how much students "looked" at the different components of the lever, the combined effects of inherently complex content, high "element interactivity," a novel interface, and the perceptual demands of constrained point-probe exploration may have imposed cognitive demands that hampered students' ability to appropriately parse and integrate this combined visual and haptic information. When one remotely explores objects or events using the rigid point-probe of a haptic device, their natural manual exploration is constrained. This perceptual limitation is due primarily to the decrease in the number and size of contact areas between the user and the object caused by the point-probe itself and the approximations built into the computer models being explored (Lederman & Klatzky, 2004). Feedback must be timely, unambiguous, and useful for it to contribute to learning (Sweller, 1988). The haptic feedback, in this case, may simply have not risen to this level.

Although it has become generally accepted that our visual and haptic perceptual systems are inextricably intertwined, the exact nature and functioning of this association is not fully known. There is neurological evidence that haptic information is processed similarly to visual information (Sathian, 1998) and the use of visual plus haptic feedback in the present study may have contributed to an increase in cognitive load that reduced integration needed for participants' conceptual understanding. This heavy load would likely only be exacerbated with the young adolescents participating in this study.

5.3. Conclusions and future work

With the design of this study, the addition of haptic feedback seemed to offer little in the way of additional support for learning. The Haptic + Visual group seemed to rely on visual feedback as much as haptic information. Furthermore, the additional cognitive load of receiving and coordinating the haptic feedback may even have been detrimental to learning. However, this is clearly a preliminary study that should be interpreted with caution until further studies can be conducted.

The results of this study point to a need for continued analysis of the data collected in this study and the beginning of a design study where new iterations of the virtual lever lab are developed based on research findings. Not surprisingly, design of a virtual lever lab that promotes conceptual understanding is neither simple nor straightforward. This study has used a research-based approach to look at what does and does not work in promoting learning. Future work will continue to refine our understanding of the inclusion of advanced technologies in science education. Of particular interest will be the continued exploration of the use of embedded assessments to more accurately capture the impact of haptics on learning. In addition, further methodological refinements are needed to leverage eye tracking data as a means of understanding haptic interaction. For example, it may be possible to conduct a hierarchic log-linear analysis to better understand the contributions of specific transitions between look zones (Gottman & Roy, 1990). Finally, expanded trials are needed to more fully uncover the contribution of haptics to learning in virtual labs like the one designed for this study.

As more and more science activities become virtualized through the use of computer-based modeling and simulation technologies, it is crucial that researchers continue to strive to understand what impact—positive and negative—these tools have on learning, as well as the complicated relationships between haptic and visual perception and information processing. This research represents a systematic "first pass" at trying to better understand what the impact of haptic feedback is on learning about levers via a computer-based virtual lab. Further, this work signifies a move into what Stokes (1997) referred to as the "use-inspired basic research" portion of Pasteur's quadrant, research that links basic research on haptic perception and cognition with the research on haptics as an intervention for change.

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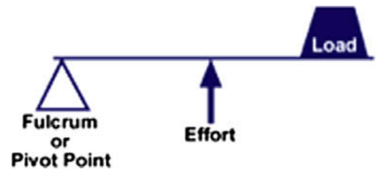
Appendix A. Sample test items

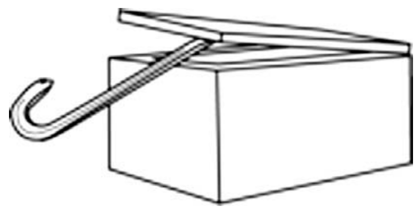
(1) Suppose that you had to explain what a ***lever*** is to a younger student...What would you say or do to help them understand levers?

Use the space below. Feel free to draw a picture to aid your explanation.

(2) The diagram below represents a _________________ lever.
- (A) first class
- (B) second class
- (C) third class
- (D) fourth class



(3a) The picture below shows an example of a:



(A) first class lever
(B) second class lever
(C) third class lever

(3b) Why did you choose the answer that you did?____

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