Original article

doi: 10.1111/jcal.12024

Journal of Computer Assisted Learning

Relative effectiveness of physical and virtual manipulatives for conceptual change in science: how falling objects fall

A.W. Lazonder & S. Ehrenhard

Department of Instructional Technology, University of Twente, Enschede, the Netherlands

Abstract This study offers new insights into the ongoing debate about whether physical and virtual materials are equally effective in inquiry-based science instruction. Physical materials were predicted to have a surplus value when haptic feedback helps discern object characteristics or when the perceived credibility of experimental data can impede conceptual change. Both assumptions were tested by comparing the belief revisions and confidence ratings of children ($n = 60$) engaged in an inquiry task about falling objects. Children were assigned to one of three instructional conditions that differed with regard to the type of materials and the possibility to manipulate those materials. Main findings confirmed the alleged benefits of physical manipulation in correcting misconceptions about object characteristics that are perceived by touch. Belief revision about visually discernible characteristics proved independent of the type of material and type of manipulation, as was children's confidence in their post-instructional beliefs. Together, these findings indicate that tactile cues derived from physical manipulation can have a unique contribution to children's science learning.

Keywords conceptual change, hands-on science, inquiry learning, simulations.

Introduction

Back in the early 1980s, science teachers could enliven their lessons by demonstrating an experiment in class or having children perform that experiment themselves in the school lab. The latter option, although time and labour intensive, was generally believed to be more effective as it would increase learning and motivation, and help develop a more positive attitude towards science (Glasson, 1989; Riley, 1979). Nowadays, computer and Internet technology has found its way into the classroom and offers science teachers a wide range of simulations and animations to let children observe or conduct science experiments. Using these virtual environments certainly requires less preparation and classroom time. But will students learn as much from simulated and real-life experiments?

Using simulations for educational experimentation has some clear advantages over using real materials. These include an increased accuracy and efficiency in gathering and analysing data, and visualization of otherwise concealed phenomena through features such as animation, slow replay and force vectors (Feisel & Rosa, 2005; Hofstein & Lunetta, 2003). The expressed downside of simulation-based inquiry learning is the limited attention to lab ethics and safety procedures, the limited exposure to biased measurements and

Accepted: 26 April 2013
Correspondence: Ard Lazonder, Department of Instructional Technology, University of Twente, PO Box 217, 7500 AE Enschede, the Netherlands. Email: a.w.lazonder@utwente.nl

© 2013 John Wiley & Sons Ltd

'noisy' data, and the limited potential to arouse excitement and curiosity (Balamuralithara & Woods, 2009). The instructional consequences of these merits and demerits are still unclear: some studies showed that virtual experimentation is more effective than real experimentation (e.g., Chang, Chen, Lin, & Sung, 2008; Finkelstein *et al.*, 2005), other studies report in favour of real experimentation (Zacharia, Loizou, & Papaevripidou, 2012), and yet other studies found that the two are equally effective (e.g., Corter, Esche, Chassapis, Mac, & Nickerson, 2011; Renken & Nunez, 2013; Yuan, Lee, & Wang, 2010). So what could explain these differential effects?

This question has divided scholars and practitioners for quite some time, and the answer is to some extent still unclear. The Kozma–Clark debate in the early 1990s set the stage for an ongoing discussion about whether the use of media, or presentation form in general, influences student achievement. Simply put, Clark (1994) argued that any learning effect of media is due to the instructional method associated with the use of that media. Kozma (1991, 1994) challenged this claim because it did not account for the fact that information processing depends on input modality, which varies among different media.

Kozma's view is shared by educational theorists such as Flick (1993), and echoed in professional journals that point science teachers to the benefits of having children manipulate tangible materials (e.g., Steinberg, 2000). The core argument of the 'Kozma-adherents' is that physical interaction enhances learning because it might provide additional sources of brain activation that facilitates retention and retrieval. Unlike virtual learning materials, physical materials can be touched, smelled, inspected from different angles and manipulated in three-dimensional space. To illustrate, using physical materials in a springs-and-weights task enables children to grasp the items with their hands to literally feel the relation between density, volume and mass – an experience that would be impossible to get from manipulating virtual materials with a computer mouse (Marshall, 2005). Physical manipulatives are therefore assumed to be effective because they offer a unique kind of sensory input that can be beneficial to learning.

Cognitive psychologists hold a more balanced view on the effectiveness of concrete learning materials. On the positive side, concrete materials can facilitate both the acquisition of abstract concepts and the inductive and deductive reasoning processes that are a key to inquiry-based learning (Bruner, Goodnow, & Austin, 1956; Lazonder, Wilhelm, & Van Lieburg, 2009; Wason & Shapiro, 1971). The drawback of concreteness is that learners often fail to recognize the abstract principle underlying a concrete problem or situation and transfer that principle to another concrete situation (Gick & Holyoak, 1980). A gradual increase of abstractness (or a fading of concreteness) during the learning process could help solve this issue (Goldstone & Son, 2005; Salomon & Perkins, 1989).

Another perspective on the purported effectiveness of physical manipulation is derived from, or influenced by, Piaget's (1960) theory of cognitive development. Active manipulation of physical materials plays an essential role in Piaget's theory, in particular during the initial and intermediate developmental stages. Children in upper elementary education, who are in the concrete operational stage, can think logically with concrete objects but are still incapable of abstract reasoning. Even though Piaget obviously could not consider whether children this age would be able to reason equally well with concrete materials as with their digital equivalents, his theory has often been (mis)used to advise against using virtual materials in hands-on science education because '. . . abstractions, ideas not tied to the concrete and manipulable, are inaccessible to concrete operational children' (Metz, 1995, p. 95).

There is, however, surprisingly little evidence that the theoretical accounts described above hold true. Despite the growing popularity of neuroscience in education, research into the alleged effects of physical manipulation on brain activation is, to our knowledge, still lacking. In addition, the early studies that compared physical and virtual manipulatives in terms of learning processes and outcomes generally confound instructional methods and media, thereby supporting Clark's (1994) argument that any learning effect of media is due to the method of instruction. This notion instigated Triona and Klahr (2003) to isolate the effect of physical manipulation from the method of instruction. Their study compared the effectiveness of a physical and virtual version of the springs-and-weight task that differed only in the medium of presentation. Results showed no differential effects of the type of manipulation on the development of experimentation and prediction skills (which were the main learning

© 2013 John Wiley & Sons Ltd

outcomes) and children's confidence in the conclusions they could draw from their investigations. A follow-up study proved that physical and virtual manipulatives are equally effective in producing gains in children's topical knowledge, their ability to design unconfounded experiments and in their confidence in their knowledge (Klahr, Triona, & Williams, 2007).

These findings have been replicated in different domains and with different age groups (Jaakkola & Nurmi, 2008; Ketelhut & Nelson, 2010; Winn *et al.*, 2006; Zacharia & Olympiou, 2011). Other studies have explored how physical and virtual manipulation can best be combined. Their accumulated findings show that any combination of physical and virtual experimentation produces higher learning gains than either of its constituents (Chini, Madsen, Gire, Rebello, & Puntambekar, 2012; Jaakkola, Nurmi, & Veermans, 2011; Olympiou, Zacharia, & De Jong, 2013; Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008). As these studies diverge on how both types of manipulation can best be combined, this outcome seems attributable to the benefits of using multiple representations rather than the superiority of handling one type of material over the other.

However, none of these studies differentiated the type of sensory input needed to perceive how the objects and materials used in the children's investigations differ from one another. To illustrate, Klahr *et al.* (2007) had children design mousetrap cars that differed with regard to the length of the body, the size of the wheels and the thickness of the axe. All of these components vary on dimensions that are visually discernible and hence rely less on physical manipulation than, for instance, mass or surface structure would. Triona and Klahr (2003) did include mass as one of the factors children should find out about, but their study did not intend to assess whether children learned more about this factor through physical or virtual manipulation. Still, touch in particular could provide important additional information that cannot be obtained by the other senses. It might therefore be that physical manipulation is more effective than virtual manipulation if objects rely heavily or exclusively on tactile cues for recognition.

Physical manipulation might also be advantageous in case children hold false beliefs about the topic they are investigating. Zacharia *et al.* (2012) recently showed that children are more likely to correct their misconceptions when experimenting with physical materials than virtual materials. Even though the reason underlying this effect could not be established from the data, children's faith in the fidelity of the simulation might be a factor. There is widespread evidence that children discount conflicting data in various ways to protect their incorrect initial beliefs (e.g., Chinn & Brewer, 1998; Mason, 2001). Virtual materials can provide strong reasons to disbelieve contradictory findings. Children might, for instance, ignore the data for reasons of validity (e.g., computer simulations are not real, so why bother?), reject the data by appealing to methodological flaws (e.g., falling objects on a computer screen have no air resistance) or reinterpret the evidence to match their initial beliefs (e.g., this is true in an ideal, virtual world, but in reality things work differently). The authenticity of physical materials could thus promote conceptual change by increasing the perceived credibility of the data (cf. Srinivasan *et al.*, 2006).

To summarize, prior research has shown that it generally makes little difference whether children experiment with physical or virtual materials. It is conceivable, however, that physical manipulatives are more effective when tactile information is needed to discern objects and materials or when credibility issues are likely to impede learning. Both assumptions were tested in an experimental study that investigated children's responses to conflicting scientific data.

Research design and hypotheses

The present study investigated children engaged in an inquiry task about falling objects – a topic many children hold false beliefs about (e.g., Chinn & Malhotra, 2002; Howe, Taylor Tavares, & Devine, 2012). This task addressed three factors that could or could not have an effect on how fast objects fall to the ground. Two of these factors (object size and drop height) were visually discernible; the third factor (mass) was not and could only be established by holding the objects in one's hands. Children investigated the influence of these factors in one of three instructional conditions that differed with regard to the type of materials that was used (physical or virtual) and the possibility to manipulate the materials. Children in the *physical manipulation* condition engaged in hands-on experiments with concrete, tangible materials. Children in the

© 2013 John Wiley & Sons Ltd

Table 1. Attributes of the Objects Used in the Task

	Ping-pong ball		Tennis ball		Soccer ball	
	Light	Heavy	Light	Heavy	Light	Heavy
Mass	3.0 g	20.0 g	58.0 g	275.0 g	275.0 g	867.0 g
Size (Ø)	4.0 cm	4.0 cm	6.6 cm	6.6 cm	22.0 cm	22.0 cm

virtual manipulation condition could conduct the same experiments using a computer simulation whereas children in the *physical demonstration* condition could watch an instructor conduct these experiments with concrete materials.

Two hypotheses guided the study. The first predicted that physical materials are more effective than virtual materials in producing knowledge gains about factors that call upon tactile information for recognition. This hypothesis was tested by comparing the post-instructional beliefs of children from the physical manipulation and virtual manipulation condition about factors that either were or were not discernible by touch. The beliefs of children in the physical manipulation condition were also compared with those in the physical demonstration condition to establish the effects of tactile cues per se.

The second hypothesis stated that, when confronted with conflicting data, children experimenting with physical manipulatives consider their results more trustworthy than children who use virtual manipulatives. This effect was assumed to be independent of the type of sensory information, and examined by comparing the confidence ratings of children in the physical manipulation and virtual manipulation conditions. Confidence ratings obtained in the physical manipulation condition were also compared with those from the physical demonstration condition to confirm that this effect depends on whether or not the children conducted the experiments themselves.

Method

Participants

The sample comprised 60 elementary school children (33 boys, 27 girls) with a mean age of 10.25 years ($SD = 0.82$). Children were randomly and evenly assigned to either the physical manipulation condition, the physical demonstration condition or the virtual manipulation condition.

Experimental task and materials

Children in all three conditions were asked to investigate what determines how fast two objects fall to the ground. This task was loosely based on the rock-dropping experiment by Chinn and Malhotra (2002) and adapted to include three factors: (1) the mass of the object; (2) the size of the object; and (3) the height from which the object is dropped. Size and height were causal factors with lower values being associated with faster drop times. Mass was a non-causal factor: if a heavy and a light object of the same size were dropped from the same height, they would hit the floor at the same time.

Three sets of objects were used (see Table 1) that could be dropped from 1, respectively 2 m above the floor. The vinyl floor covering enabled children in both conditions to see as well as hear when the balls hit the floor; this auditive feedback helped discern the minor differences in drop speed. Objects within each set were similar in appearance so that children could not tell which object was heavier by looking. Differences in size between any two sets of objects were large enough to be visible to the naked eye, as was the distinction between the two drop heights. The heavy tennis ball and the light soccer ball had the exact same mass so children could conduct an unconfounded experiment to induce the influence of the factor size. To make a valid comparison among the two drop heights, two light ping-pong balls (or two light tennis balls) could be used.

Children in the physical manipulation condition received the actual items plus a stepladder to drop them from either 1 or 2 m high; height markers on the wall indicated both positions. Children in the physical demonstration condition could use these materials to design their own experiments, which were then conducted by the instructor. Children in the virtual condition worked with a computer simulation of the same sets of objects. The simulation interface (see Figure 1) displayed real-

© 2013 John Wiley & Sons Ltd

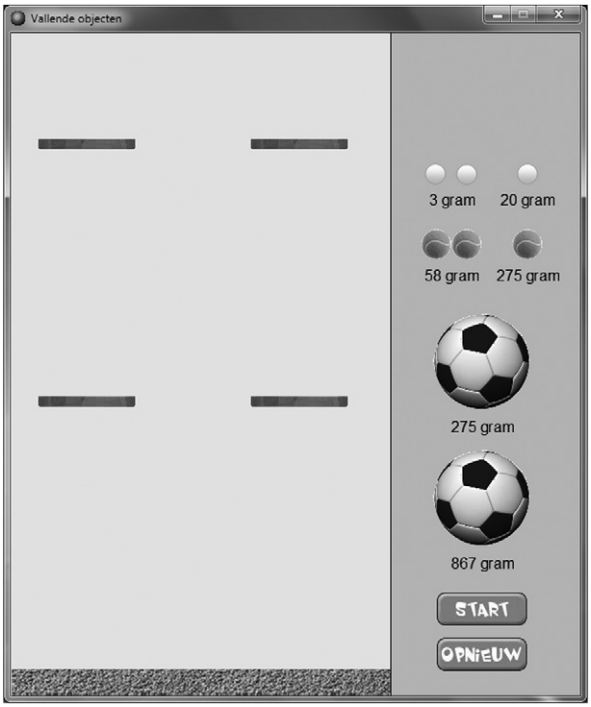

Figure 1 Interface of the Simulation Used by Children in the Virtual Manipulation Condition

istically scaled photographic images of the balls and drop heights. Children could experiment with the simulation by dragging two balls from the right side of the screen to one of the shelves in the left pane. Clicking the 'Start' button would cause the balls to drop; when they hit the floor a matching sound was played.

Beliefs questionnaire

A 3-item questionnaire gauged children's beliefs about falling objects. Each item addressed the influence of one factor. Items were closed questions that asked children to indicate whether they thought a particular factor would influence drop time and, if so, what would be the direction of effect. To illustrate, the item about the influence of mass asked 'what would happen if you drop a heavy and a light object'. Children should tick the option 'there is *no* difference in which object hits the ground first' if they thought mass had no effect on drop time. In case they thought mass did have an impact, they should tick the option 'there *is* a difference in which object hits the ground first' and, in addition, circle whether the heavy or the light object would hit first. Children's answers were scored as true or false.

Procedure

Children participated in the study one at a time. All sessions took place in a quiet room and were conducted by the same instructor (the second author) who followed the same scripted procedure in each condition. She first welcomed the child, briefly explained the purpose of the study and administered the beliefs questionnaire. The instructor then showed the materials and explained on what dimensions they varied. Children were told that they had to investigate whether and how mass, size and drop height make a difference in how fast objects fall by designing experiments in which two balls are simultaneously dropped. Children had to address these factors in an arbitrary fixed order: first size, then mass, and finally height. After these instructions, children started their investigations following a procedure that depended on the child's instructional condition.

Children in the physical manipulation condition proposed which experiments they would like to do. When necessary, the instructor would fine-tune the set-up in dialogue with the child to ensure that all experiments were unconfounded, and motivate why these adjustments were needed. Once an unconfounded experiment was designed, the child predicted which of the two objects would hit the ground first, conducted the experiment and reported the outcome. Predictions and outcomes were noted down by the instructor. Children had to perform at least one experiment per factor so they would collect data that could help resolve their misconception about each factor. There was no limit to the maximum number of experiments they could perform: children could redo an experiment if they, or the instructor, felt the balls were not simultaneously released, or when the child was unsure about his/her observation.

Children in the physical demonstration condition followed the same procedure except that they did not conduct the experiments they had designed. Instead, the instructor did the experiments for them so that the child merely had to observe which ball would hit first. Consequently, children in this condition never touched any of the materials during their investigations.

Children in the virtual manipulation condition were first acquainted with the simulation. When the operation of the software was clear, they started their investigation using the same procedure as in the physical

© 2013 John Wiley & Sons Ltd

Table 2. Number of Children with Misconceptions Before and After the Instruction

	Mass		Size	
	Before	After	Before	After
Physical manipulation	19	0	13	1
Physical demonstration	19	7	16	4
Virtual manipulation	19	5	17	3

manipulation condition. The only difference was that the experiments were done with the simulation; actual items were replaced with realistically scaled photographic images of the balls and drop heights.

The closure of the session was identical in all three conditions. After children had finished their investigations, they once again completed the beliefs questionnaire. The instructor then assessed their confidence in experimental outcomes by asking whether or not they were sure about their answers. In case of a negative of noncommittal answer, the experimenter would ask them to explain the reasons for their uncertainty.

Results

Preliminary analyses were performed to establish children's pre-instructional beliefs about the three factors under study. A misconception was defined as a false belief and identified from the answers to the beliefs questionnaire. None of the children obtained a perfect score on this questionnaire: the best performing children ($n = 9$) answered two items correctly which means that every child had one or more misconceptions. Frequency counts further showed that 18 of the 60 children (33%) held a misconception about the factor height; the number of children with misconceptions about the factors mass ($n = 57$) and size ($n = 46$) was substantially higher. As misconceptions about height were too few for meaningful statistical analysis, it was decided to exclude this factor and focus on mass and size instead. Table 2 shows a cross-tabulation of these misconceptions by condition. Chi-square test of independence ascertained that children with and without a misconception about mass were equally distributed among the three instructional conditions, $\chi^2(2,\ N = 60) = 0.00$, $p = 1.000$. The number of initial misconceptions about the factor size was comparable in all three conditions as well, $\chi^2(2, N = 60) = 2.42$, $p = 0.298$.

Children's investigations were analysed to indicate whether the three instructional regimes invoked comparable inquiry performance. Results showed that children conducted four experiments on average to investigate the factors they had misconceptions about. The minor cross-condition differences shown in Table 3 were not statistically significant, $F(2,\ 57) = 0.40$, $p = 0.673$. Consistent with the outcomes of the beliefs questionnaire, most of these experiments (92%) were accompanied by an incorrect prediction. The proportion of incorrect predictions was comparable across conditions, $F(2,\ 57) = 0.44$, $p = 0.649$. As incorrect predictions might bias children's judgment of the data, it was examined whether observations made during the experiment were in line with the actual outcomes. This proved to be the case: children in all three conditions observed and reported the correct results of 94% of their experiments. Instructional condition had no effect on the proportion of correct observations, $F(2, 57) = 0.13$, $p = 0.877$.

Table 3. Means (and SD) for Children's Performance during the Instruction

	Experiments[a]	Incorrect predictions[b]	Correct observations[b]
Physical manipulation	3.75 (1.62)	0.94 (.13)	0.92 (.14)
Physical demonstration	4.20 (1.51)	0.93 (.16)	0.93 (.13)
Virtual manipulation	4.05 (1.73)	0.88 (.25)	0.95 (.22)

[a]Mean number of trials conducted to investigate the factors mass and size. [b]Relative to the number of experiments (proportions).

© 2013 John Wiley & Sons Ltd

Table 4. Synthesis of Children's Overall Conceptions Before and After Their Investigations

	Post-test				
Pre-test	1	2	3	4	5
1. No misconceptions ($n = 0$)	0.00	0.00	0.00	0.00	0.00
2. 'Mass-is-all' misconceptions ($n = 16$)	0.69	0.00	0.13	0.06	0.13
3. Mass-consistent misconceptions ($n = 32$)	0.66	0.00	0.28	0.06	0.00
4. Mass-inconsistent misconceptions ($n = 8$)	0.63	0.00	0.13	0.25	0.00
5. Miscellaneous misconceptions ($n = 4$)	0.50	0.00	0.00	0.00	0.50

Note. Cell entries represent the proportion of children with a particular initial conception (rows) who ended their session with the final conception indicated in the columns.

Table 4 summarizes how these investigations changed children's overall conceptions about the impact of mass and size. The majority of the children (80%) initially had a weight bias: 16 children believed mass to be only influential factor (heavier objects fall fastest, object size has no effect) and 32 children held mass-consistent beliefs about size (e.g., if heavy objects fall faster, then larger objects fall faster too). Regardless of their initial misconceptions, most children (50%–69%) ended their sessions with a correct overall understanding. Of the 19 children who did not, 12 kept on believing that mass matters but none of them considered it to be the sole factor. There were in fact only three children who eventually failed to acknowledge the influence of object size.

Table 2 gives a more detailed account of how many children in each condition changed their misconceptions after the instruction. (Correct initial beliefs were generally maintained; there was only one child who changed his correct initial conception about the factor size into a misconception.) The majority of the children (83%) corrected their initial misconceptions about the factor size, and the chance of this to happen proved to be independent of instructional condition, $\chi^2(2, N = 46) = 1.50$, $p = 0.473$. Revision of misconceptions about mass occurred nearly as often (79%) and *did* depend on instructional condition, $\chi^2(2, N = 57) = 8.23$, $p = 0.016$. Relative benefit increase (RBI) ratios were used to determine the differences among the three conditions. RBI indicates the increase in rates of good outcomes between two groups and was calculated as $(\%\text{success}_{\text{group A}}/\%\text{success}_{\text{group B}}) - 1$. Comparison among the two conditions that employed physical materials yielded a RBI of 0.55 in favour of the physical manipulation condition. This means that the chance of revising a misconception about mass increases by 55% if children can do their experiments hands-on instead of watching someone else conduct the experiments for them. The RBI comparing the physical manipulation condition to the virtual manipulation condition indicated that handling physical materials yields 53% more chance of correcting this misconception than working with virtual materials.

Confidence ratings aimed to indicate whether children were sure about their answers on the final beliefs questionnaire. Confidence was assessed by a single dichotomous question that, in case of a negative or noncommittal answer, would be complemented with open-ended questions to find out the reason underlying the child's scepticism. Without exception, however, all children firmly declared that they were confident in their answers. Given these unanimously positive responses, the prepared follow-up questions had become irrelevant. Statistical analysis of the confidence ratings was not possible due to the complete lack of variation in scores.

Discussion

When children engage in hands-on science activities, it generally makes little difference whether they experiment with physical or virtual materials. It is conceivable, however, that physical manipulation has an advantage in cases where tactile cues provide information that cannot be obtained by the other senses or when learning is impeded by the credibility of the findings children collect through their inquiry. The outcomes of the present study, in short, substantiate the first assumption but lend no support to the second.

A closer look on the study's findings helps shed more light on the relative effectiveness of physical and virtual materials. Consistent with our first hypothesis,

© 2013 John Wiley & Sons Ltd

all three instructional regimes proved equally effective to learn about the influence of object size – a characteristic that children in all conditions could readily perceive by looking. With mass, however, tactile information provided additional cues to 'grasp' the difference between objects, and misconceptions about this factor were corrected more often in the physical manipulation condition than in the physical demonstration condition. As children in the physical manipulation condition also had more mass-related belief revisions than children from the virtual manipulation condition, perceiving this additional information by touch is more effective than reading that same information on a computer screen.

An alternative explanation might be that children in the virtual manipulation condition protected their initial misconceptions by discounting the data from the simulation. Our second hypothesis predicted that this would be the case, but the children's confidence ratings seem to prove otherwise. All children expressed great confidence in their answers to the post-instructional beliefs questionnaire, and there was no difference among the three conditions. Even though the observed ceiling effect does not allow for any definitive conclusion, these findings suggest that children with false beliefs consider virtual experiments as trustworthy as physical ones, and that children's confidence in their beliefs is independent of whether they conduct the experiments themselves or observe the experiments being done by another person.

Together, these findings confirm and extend the work of Zacharia *et al.* (2012). They also found that children who hold misconceptions about mass learn more from experimenting with physical materials, and concluded that physicality is a prerequisite to conceptual change. Our comparison among the physical manipulation and physical demonstration condition nevertheless shows that physicality as such is insufficient. Rather, it is the *manipulation* of physical materials that promotes children's belief revisions. The reason why physical manipulation is superior in case of misconceptions only could not be established from the present findings. It does seem, however, that children's confidence in the insights gained from interacting with the simulation does not account for this differential effect. Future research should therefore try to uncover the true reason behind this intriguing result.

These studies should consider using a more sophisticated confidence measure. As confidence is an abstract and hence difficult concept for children, it was assessed by a single straightforward question. Both differentiating between the three factors and motivating a positive answer was thought to be beyond the children's capabilities. The observed ceiling effect nevertheless raises some doubt as to what this question actually measured. Future studies should therefore consider alternative ways to assess children's confidence, and validate their measurements through pilot testing.

Future research might also examine whether children maintain their newly acquired beliefs. Even though this study showed that physical manipulation has an immediate effect on learning, it is still unknown whether these initial advantages are sustained over time. Theoretical evidence suggests that this may be the case (Barsalou, 1999; Minogue & Jones, 2006). When handling physical materials, both visual and tactile cues can be encoded in memory and thus form a more elaborate representation than information from a single sensory channel. As more elaborate encoding facilitates information retrieval, children who manipulate physical materials during the experiment are more likely to remember the outcomes after the experiment. Whether these theoretical predictions hold true could be established in future research.

Another suggestion for future research would be to investigate the relative effectiveness of real-life and simulated inquiry learning environments under more ecologically valid circumstances. The simulation in the present study was designed as the digital equivalent of the physical manipulation condition, and therefore lacked some of the unique affordances virtual learning environments can offer (e.g., systematic numerical output, force vectors, slow replay). Augmenting the simulation with these features and comparing its effectiveness with real experimentation would strengthen the practical applicability of the present findings. Initial evidence suggests that these features do not necessarily enhance learning (Renken & Nunez, 2013), but more research is needed.

The present findings could also be an incentive to software developers who seek to incorporate haptic feedback in virtual learning environments. Most of the existing simulations in science education use only visual and auditory feedback, but recent attempts have succeeded to create haptic augmented simulations that

© 2013 John Wiley & Sons Ltd

enable learners to actually feel tactical sensations of friction, force and motion (e.g., Jones, Minogue, Tretter, Negishi, & Taylor, 2005). This haptic feedback is generally provided through a mouse, a joystick or via a touch screen, and emerging mobile technologies can extend the possibility to mimic tactile experiences even further. Technological advances like these can create more immersive virtual learning environments that might be equally beneficial to learning as manipulating physical objects. Initial results obtained with elementary school children have been promising (Han & Black, 2011) and arouse one's curiosity about the comparison of experimenting with haptic simulations and physical materials.

Practical implications pertain to elementary schoolteachers who use inquiry-based activities in their science lessons. Contrary to the prevailing view that children learn as much from physical and virtual experimentation, the present findings recommend using the former in case children hold incorrect beliefs about a topic for which tactile feedback plays a role. The underlying reason is that neither virtual experimentation nor in-class demonstrations can provide the haptic experiences that appear to contribute to belief revision. If on the other hand all necessary information about the topic can be obtained by the other senses, teachers can choose the methods and materials of their own liking as manipulating physical materials in the school lab, working with virtual labs, and watching teacher demonstrations yield an equal chance that conceptual change will occur.

References

Balamuralithara, B., & Woods, P. C. (2009). Virtual laboratories in engineering education: The simulation lab and remote lab. *Computer Applications in Engineering Education*, *17*, 108–118. doi:10.1002/cae.20186

Barsalou, L. W. (1999). Perceptual symbol systems. *The Behavioral and Brain Sciences*, *22*, 577–660.

Bruner, J. S., Goodnow, J. J., & Austin, G. A. (1956). *A study of thinking*. New York, NY: Wiley.

Chang, K. E., Chen, Y. L., Lin, H. Y., & Sung, Y. T. (2008). Effects of learning support in simulation-based physics learning. *Computers & Education*, *51*, 1486–1498. doi:10.1016/j.compedu.2008.01.007

Chini, J. J., Madsen, A., Gire, E., Rebello, N. S., & Puntambekar, S. (2012). Exploration of factors that affect the comparative effectiveness of physical and virtual manipulatives in an undergraduate laboratory. *Physical Review Special Topics – Physics Education Research*, *8*, 1–12. doi:10.1103/PhysRevSTPER.8.010113

Chinn, C. A., & Brewer, W. F. (1998). An empirical test of a taxonomy of responses to anomalous data in science. *Journal of Research in Science Teaching*, *35*, 623–654. doi:10.1002/(SICI)1098-2736(199808)35:6<623:AID-TEA3>3.0.CO;2-O

Chinn, C. A., & Malhotra, B. A. (2002). Children's responses to anomalous scientific data: How is conceptual change impeded? *Journal of Educational Psychology*, *94*, 327–343. doi:10.1037/0022-0663.94.2.327

Clark, R. E. (1994). Media will never influence learning. *Educational Technology Research and Development*, *42*, 21–29.

Corter, J. E., Esche, S. K., Chassapis, C., Mac, J., & Nickerson, J. V. (2011). Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. *Computers & Education*, *57*, 2054–2067. doi:10.1016/j.compedu.2011.04.009

Feisel, L. D., & Rosa, A. J. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*, *94*, 121–130. doi:10.1002/j.2168-9830.2005.tb00833.x

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., . . . LeMaster, R. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physical Review Special Topics – Physics Education Research*, *1*, 010103. doi:10.1103/PhysRevSTPER.1.010103

Flick, L. B. (1993). The meanings of hands-on science. *Journal of Science Teacher Education*, *4*, 1–8.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306–355.

Glasson, G. E. (1989). The effects of hands-on and teacher demonstration laboratory methods on science achievement in relation to reasoning ability and prior knowledge. *Journal of Research in Science Teaching*, *26*, 121–131. doi:10.1002/tea.3660260204

Goldstone, R. L., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *The Journal of the Learning Sciences*, *14*, 69–110. doi:10.1207/s15327809jls1401_4

Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education*, *57*, 2281–2290. doi:10.1016/j.compedu.2011.06.012

Hofstein, A., & Lunetta, V. N. (2003). The laboratory in science education: Foundations for the twenty-first century. *Science Education*, *88*, 28–54. doi:10.1002/sce.10106

© 2013 John Wiley & Sons Ltd

Howe, C., Taylor Tavares, J., & Devine, A. (2012). Everyday conceptions of object fall: Explicit and tacit understanding during middle childhood. *Journal of Experimental Child Psychology*, *111*, 351–366. doi:10.1016/j.jecp.2011.09.003

Jaakkola, T., & Nurmi, S. (2008). Fostering elementary school students' understanding of simple electricity by combining simulation and laboratory activities. *Journal of Computer Assisted Learning*, *24*, 271–283. doi:10.1111/j.1365-2729.2007.00259.x

Jaakkola, T., Nurmi, S., & Veermans, K. (2011). A comparison of students' conceptual understanding of electric circuits in simulation only and simulation-laboratory contexts. *Journal of Research in Science Teaching*, *48*, 71–93. doi:10.1002/tea.20386

Jones, M. G., Minogue, J., Tretter, T. R., Negishi, A., & Taylor, R. (2005). Haptic augmentation of science instruction: Does touch matter? *Science Education*, *90*, 111–123. doi:10.1002/sce.20086

Ketelhut, D. J., & Nelson, B. C. (2010). Designing for real-world scientific inquiry in virtual environments. *Educational Research*, *52*, 151–167. doi:10.1080/00131881.2010.482741

Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching*, *44*, 183–203.

Kozma, R. B. (1991). Learning with media. *Review of Educational Research*, *61*, 179–211.

Kozma, R. B. (1994). Will media influence learning? Reframing the debate. *Educational Technology Research and Development*, *42*, 7–19.

Lazonder, A. W., Wilhelm, P., & Van Lieburg, E. (2009). Unraveling the influence of domain knowledge during simulation-based inquiry learning. *Instructional Science*, *37*, 437–451. doi:10.1007/s11251-008-9055-8

Marshall, P. (2005). Tangibles in the balance: A comparison of physical and screen versions of the balance beam task. *Proceedings of the 8th Human-Centered Technology Postgraduate Workshop. Cognitive Science Research Paper 576*, University of Sussex.

Mason, L. (2001). Responses to anomalous data on controversial topics and theory change. *Learning and Instruction*, *11*, 453–483. doi:10.1016/S0959-4752(00)00042-6

Metz, K. E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research*, *65*, 93–127.

Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research*, *76*, 317–348.

Olympiou, G., Zacharia, Z., & De Jong, T. (2013). Making the invisible visible: Enhancing students' conceptual understanding by introducing representations of abstract objects in a simulation. *Instructional Science*, *41*, 575–596. doi:10.1007/s11251-012-9245-2

Piaget, J. (1960). *The child's conception of physical causality*. Totowa, NJ: Littlefield, Adams.

Renken, M. D., & Nunez, N. (2013). Computer simulations and clear observations do not guarantee conceptual understanding. *Learning and Instruction*, *23*, 10–23. doi:10.1016/j.learninstruc.2012.08.006

Riley, J. P. (1979). The influence of hands-on science process training on preservice teachers' acquisition of process skills and attitude toward science and science teaching. *Journal of Research in Science Teaching*, *16*, 373–384. doi:10.1002/tea.3660160502

Salomon, G., & Perkins, D. N. (1989). Rocky roads to transfer: Rethinking mechanisms of a neglected phenomenon. *Educational Psychologist*, *24*, 113–142.

Srinivasan, S., Perez, L. C., Palmer, R. D., Brooks, D. W., Wilson, K., & Fowler, D. (2006). Reality versus simulation. *Journal of Science Education and Technology*, *15*, 137–141.

Steinberg, R. N. (2000). Computers in teaching science: To simulate or not to simulate? *American Journal of Physics*, *68*, S37–S41.

Triona, L. M., & Klahr, D. (2003). Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary schools students' ability to design experiments. *Cognition and Instruction*, *21*, 149–173.

Wason, P. C., & Shapiro, D. A. (1971). Natural and contrived experience in a reasoning problem. *The Quarterly Journal of Experimental Psychology*, *23*, 63–71.

Winn, W., Stahr, F., Sarason, C., Fruland, R., Oppenheimer, P., & Lee, Y.-L. (2006). Learning oceanography from a computer simulation compared with direct experience at sea. *Journal of Research in Science Teaching*, *43*, 25–42. doi:10.1002/tea.20097

Yuan, Y., Lee, C.-Y., & Wang, C.-H. (2010). A comparison study of polyominoes explorations in a physical and virtual manipulative environment. *Journal of Computer Assisted Learning*, *26*, 307–316. doi:10.1111/j.1365-2729.2010.00352.x

Zacharia, Z. C. (2007). Comparing and combining real and virtual experimentation: An effort to enhance students' conceptual understanding of electric circuits. *Journal of Computer Assisted Learning*, *23*, 120–132. doi:10.1111/j.1365-2729.2006.00215.x

Zacharia, Z. C., Loizou, E., & Papaevripidou, M. (2012). Is physicality an important aspect of learning through science

© 2013 John Wiley & Sons Ltd

experimentation among kindergarten students? *Early Childhood Research Quarterly*, *27*, 447–457. doi:10.1016/j.ecresq.2012.02.004

Zacharia, Z. C., & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction*, *21*, 317–331. doi:10.1016/j.learninstruc.2010.03.001

Zacharia, Z. C., Olympiou, G., & Papaevripidou, M. (2008). Effects of experimenting with physical and virtual manipulatives on student's conceptual understanding in heat and temperature. *Journal of Research in Science Teaching*, *45*, 1021–1035.

© 2013 John Wiley & Sons Ltd