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Physical vs. Virtual Representations Within Concreteness Fading for Primary School Computing

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***Abstract*—Computing concepts are often introduced to children using interactive concrete representations, such as Computer Science Unplugged (CSU) activities - an approach that may positively affect attitudes towards computing when applied in extra-curricular settings. However, within the classroom, children may be required to interact with abstract representations, e.g. during programming tasks, and little is known about how to design CSU activities that support this. Prior work in mathematics and computing suggests that the Theoretical Model of Concreteness Fading (TMCF) may effectively scaffold the progression from concrete to abstract and improve learning outcomes. This paper aims to investigate one of the TMCF recommendations: the use of physical manipulatives, motivated by the growing body of evidence that suggests that virtual manipulatives can, in many contexts, be equally effective while providing several design advantages. An experiment was conducted with 48 children to compare two alternative implementations of Concreteness Fading learning materials: physical concrete (Playmobil toys) vs. virtual concrete (an AR iPad app), on learning gains and attitudinal change. Using these materials, children were taught the fundamentals of network structure and internet routing. Results indicated no significant difference between groups on either measure.**

Keywords—Concreteness Fading, Computing Education, Interactive Learning Environments, Interface Design

I. Introduction

Concrete representations, such as contextualisations, metaphors, notional machines [1] and physical manipulatives (PMs), have a long history of use in the computing classroom [2]. A popular example of this approach is the CS Unplugged (CSU) project [3]. Given the recent surge of interest in computational thinking, CSU has provided many children with access to concepts that, in abstract form, may otherwise be considered complex and unengaging. For an overview of the key issues when teaching programming to novices, see [4]. Robins identifies the need for learners to master both declarative and practical knowledge, manage high levels of cognitive load derived from the inherent complexities of the topic, and develop appropriate and effective mental models. The latter is an ever-challenging area, namely helping children understand abstract representations of otherwise hidden structures and activities inside computing systems.

CSU activities have been applied successfully in various contexts, from widening participation to the professional development of teachers. However, there have been few attempts to evaluate CSU within the classroom, and existing studies show mixed results for the effect on both learning and attitudes towards computing. Bell & Vahrenhold suggest that many of these findings may have been the consequence of a "self-contained curriculum that completely rejects the use of computers" and suggest that CSU should be used "in conjunction with conventional programming lessons" [5].

Children often use PMs to learn abstract concepts in other contexts, such as mathematics and science. However, learners may find it difficult to translate between multiple representations [6]. Inspired by Bruner's Modes of Representation [7], the Theoretical Model of Concreteness Fading (TMCF) supports translation by scaffolding the identification and linking of referents between concrete and abstract [8] via at least one intermediate representation. This gradual perceptual fade has shown promising effects in mathematics [9] and computing [10]. However, empirical validation is ongoing, with Fyfe & Nathan stating six hypotheses requiring further work [11]. This paper investigates one of these hypotheses: "A Concreteness Fading progression that includes a physical manipulative in the first stage will be more effective than one that does not".

Outside the context of the TMCF, embodied cognition theorists often argue for the learning benefits of physical interaction [12], and CSU-style activities have proven popular with teachers, with many believing that physical engagement is conducive to learning [13]. However, in the context of mathematics, while meta-analysis shows PMs may be superior to abstract representations alone [14], a meta-analysis of comparisons between PMs and virtual manipulatives (VMs) shows a small effect in favour of the latter [15]. Studies have also demonstrated no significant difference between PMs and VMs for learning in a range of domains, such as chemistry [16], physics [17], and engineering [18].

This paper reports on a quantitative study in the context of teaching children aged 9 to 10 the fundamentals of network structure and internet routing. A previously evaluated physical concrete representation was compared against a closely matched virtual concrete representation, implemented as an augmented reality iPad application. Two research questions and hypotheses were investigated. **Research Question 1:** How does the physicality of the concrete representation affect learning gains? **Hypothesis 1:** The physical concrete group will have higher learning gains than the virtual concrete group. **Research Question 2:** How does the physicality of the concrete representation affect attitudes towards computing? **Hypothesis 2:** There will be a difference in attitudinal change between the physical and virtual concrete groups.

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II. Related Work

A. Concrete Learning Approaches in Primary Computing

Since 2014, English primary schools have been required to provide children aged 5 to 11 with a computing education [19] that extends beyond programming to include a wide range of computing and computational thinking concepts [20]. In support of this challenging new curriculum, teachers and researchers collaborate to provide guidance and exemplary lesson plans through the Computing at Schools (CAS) [21] network. Recommendations often include the use of concrete learning approaches, e.g., manipulatives, contextualisation, metaphor, and enaction. For example, when learning about packet transmission, CAS suggests that children should enact the role of internet routers by writing messages on slips of paper and forwarding them from child to child [22]. Rejecting the 'programming first' view and allowing children to explore concepts informally may lower the barrier to entry for topics that would otherwise be considered too advanced, such as algorithm analysis, computability, and AI, and is typical of the CSU approach [23]. For reviews of the use of unplugged and physical activities to teach computational thinking, see [2] and [24].

B. Grounded Cognition

Recent studies in cognitive science have produced a compelling body of evidence linking knowledge with neural systems for perception, action, and emotion. Barsalou argues that upon exposure to an instance of a new concept, the patterns of neural activation that define this experience are stored as 'perceptual symbols'. During 'off-line' processing, relevant perceptual symbols are partially reactivated to simulate aspects of the original experience [25]. This process of 'cognitive simulation' is central to the model of Grounded Cognition [26]. The precise mechanisms that govern conceptual representation in the brain are an area of ongoing research and debate. However, FMRI evidence strongly supports the existence of simulation, and Martin argues that neural activity is never epiphenomenal [27]. Sceptical of the *necessity* of embodiment, Mahon and Caramazza propose that sensorimotor experience offers a supportive but unnecessary role in cognition [28]. Much of the evidence supporting grounded cognition is gathered by observing the effects of processing simple nouns and verbs in controlled settings. Further research is needed to understand the possible benefits of supporting the real-world learning of complex concepts and procedures, as found in computing, through perception, action, and emotion.

C. Empirical Studies of Physical Manipulative Use in STEM

Experiments investigating the use of physical manipulatives in the domain of physics have produced nuanced results. Kontra et al. [29] developed a physical manipulative to teach undergraduate students concepts such as torque and angular momentum. Participants were assigned to either an 'action' group (physical interaction with the manipulative) or an 'observation' group (passive observation of the action group). After guided instruction, all participants completed a post-test conducted inside an FMRI machine, with no significant between-group differences found. However, on a delayed post-test conducted within 24 hours, the action group scored significantly higher than the observation group. Most interestingly, the level of neural activation in sensorimotor areas of the brain, recorded during the immediate post-test, was higher for the action group, and this neural activity predicted performance on the delayed post-test. These results imply that physical manipulation increases cognitive simulation during complex tasks, which may lead to improved retention. Also, in the domain of physics, Johnson-Glenberg et al. investigated the effects of embodiment on undergraduates learning about centripetal force [30]. Their between-groups experiment comprised two levels of embodiment (high and low) within three distinct learning environments (mouse-driven desktop, interactive whiteboard, and the SMALLab mixed-reality system incorporating physical manipulatives and digital interactions). Learning outcomes were measured separately on declarative and generative tasks using immediate and delayed post-tests conducted one week later. Again, no differences were found between groups on the immediate post-test. The difference between scores on the immediate and delayed post-test for generative tasks was found to be significant in favour of the high embodiment groups, but no differences were found in changes to declarative task scores over time. If physical activity during learning is beneficial, one might expect studies that vary the level of physicality between groups learning the rules of angular momentum and centripetal force to be the perfect context for strong outcomes. The experiments of Kontra et al. and Johnson-Glenberg et al. found no differences in immediate learning gains, and differences in delayed learning gains were only found for specific concepts and tasks. However, neither experiment included an abstract learning group as a control, so we can only conclude that there may be an upper limit to the benefits of physicality during learning. It is important to note that cognitive simulation does not *require* physical activity at the time of learning. For example, in Kontra et al., the observation group showed neural activity in sensorimotor areas after vicarious learning.

D. Physical, Virtual and Imagined Manipulation

A further complication arises when considering how perceptual symbols become associated with language, thus triggering cognitive simulation during semantic processing. Glenberg's Indexical Hypothesis [31] states that when language is effectively associated, or 'indexed', with external (objects or images) or internal (perceptual symbols) representations, the affordances of concrete referents within that language can be combined into a coherent mental model, or 'meshed', leading to improved comprehension and performance on tasks. Glenberg argues that his model could explain findings that educational texts are more effective when combined with images [32], ideally presented to the learner with spatial [33] and temporal contiguity [33] to support indexing. In a series of experiments with children, Glenberg et al. investigated the effect of supporting indexing through physical, virtual, and imagined manipulation on reading comprehension and recall [34]. A physical manipulative was developed using children's farmyard animal toys that enabled the enaction of provided narratives. Participants were divided into three groups: manipulate-while-reading, reading-only, and a control group that only completed the final session. Across five sessions, the manipulate-while-reading group was given various levels of cues and opportunities to enact the narrative, fading from high to none, whereas the reading-only group was only permitted to observe the manipulative. After each session, participants' recall was

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measured. In four of the five sessions, results showed significant differences in recall between the manipulate-while-reading group and the reading-only group in favour of manipulation. However, in the final session, in which all participants passively observed the manipulative, there were no differences between the three groups. Glenberg et al. concluded that manipulation is very effective for indexing concrete representations to abstract referents but does not automatically lead children to develop an effective strategy to apply in their absence.

In a follow-up experiment of a similar design [34], after initial practice with the manipulative prior to the main sessions, physical manipulation was replaced with imagined manipulation. Participants in this group were shown the manipulative and then cued at specific points in the narrative to imagine enacting the current scene, followed by a discussion of the efficacy of this strategy. Results showed that the imagined manipulation group recalled significantly more than the reading-only group across all sessions. Comprehension was also measured on spatial inference and justification, with the imagined manipulation group scoring consistently higher than the reading-only group, although not always significantly. In a further follow-up experiment, Glenberg et al. compared three groups: physical-imagined manipulation, virtual-imagined manipulation (desktop computer), and reading-only [35]. Participants in both manipulation groups were first required to enact narratives physically/virtually and later using imaginary action only. Results showed that the virtual manipulative consistently produced the highest learning outcomes. When manipulation was allowed, the difference between virtual and physical was not significant, but during imagined manipulation, a significant difference emerged. Across these experiments, Glenberg's findings repeatedly demonstrate the value of grounding language in concrete experience; however, physicality showed no advantage. The support given to indexing the concrete and abstract referents is more important than the modality of concrete experience.

Similar conclusions on the relative benefit of physical and virtual manipulatives can be found in mathematics. Carbonneau et al.'s meta-analysis of 55 studies comparing instruction using physical manipulatives vs. abstract materials [14] showed that physical manipulatives led to improved learning outcomes with small to moderate effect sizes, whereas effects on retention were moderate to large. However, a further meta-analysis by Moyer-Packenham et al. compared mathematical instruction using virtual manipulatives vs physical manipulatives or classroom instruction with textbooks [15]. From 18 studies, the authors found a moderate effect size favouring virtual manipulatives over classroom instruction. More importantly, from 38 studies, virtual manipulatives were found to improve learning outcomes compared to physical manipulatives, with a small effect size. It should be noted that the analysis did not distinguish between immediate learning gains and retention.

Research is required to understand the effects of physical and virtual materials on learning and retention in computing. Based on the evidence cited from physics, English, and mathematics, one might infer that concrete learning experiences should be more effective than abstract ones. Determining whether to design a physical or virtual concrete experience is more challenging. It would appear that, for some specific concepts and tasks, the level of physicality may influence retention. In the case of the two physics learning experiments previously described, the physical manipulative provided learners with direct experience of the hidden and unintuitive forces under study. This may not be widely applicable to computing or other domains. However, the distinction made by Johnson-Glenberg et al. between declarative and generative tasks could perhaps be relevant. The learning environment described in this paper focuses on the former, but programming activities would likely be considered generative, which would require separate investigation.

E. The Theoretical Model of Concreteness Fading

The Theoretical Model of Concreteness Fading [8] offers one approach to effectively 'indexing' referents between concrete and abstract representations. Inspired by Bruner's Modes of Representation [7], Fyfe et al. recommend the sequential presentation of at least three distinct stages, fading in perceptual detail from concrete to abstract. The initial concrete stage provides learners with an intuitive, engaging, and informal introduction to a topic, similar to the activities found in the CSU collection. It also serves to create or reinforce the perceptual symbols, which are then indexed to their abstract referents during at least one intermediate stage, in which iconic representations are presented simultaneously with abstract language. In the final stage, learners apply their knowledge within a fully abstract representation. In a series of experiments, Fyfe et al. investigated this approach in the context of teaching children (aged 7 to 9) about mathematical equality using a balance scale physical manipulative [9]. In a between-groups design, participants were assigned to one of four groups: concrete representations only, abstract representations only, Concreteness Fading, or Concreteness Introduction (an abstract to concrete sequence). Results showed that Concreteness Fading led to significantly higher scores on a post-intervention transfer test than all other sequences. Interestingly, Concreteness Introduction did not lead to significantly different scores compared to the two non-fading sequences, implying that the direction of fading is important. The Concreteness Fading approach has been evaluated in a variety of domains with mixed results. However, these findings may be caused by ineffective indexing resulting from representational sequences that deviate from the model suggested by Fyfe et al., as Suh's review shows [36].

F. Investigating Concreteness Fading in Primary Computing

The experiment described in this paper is the second in a series of three completed studies investigating Concreteness Fading in the context of teaching children (aged 9 to 10) introductory computing concepts. In our first study, replicating the experimental groups used by Fyfe et al. [9], we compared the effect of four representational sequences on learning gains and changes in attitudes towards computing [10]. Results showed identical group ordering to Fyfe et al. and that Concreteness Fading led to significantly higher learning gains than using concrete-only materials. Between-group differences in changes in attitudes towards computing were not significant, but Concreteness Fading showed the largest improvement. In our third experiment, the augmented reality learning environment described in this paper was updated to investigate the effect of different approaches to linking (indexing) concrete

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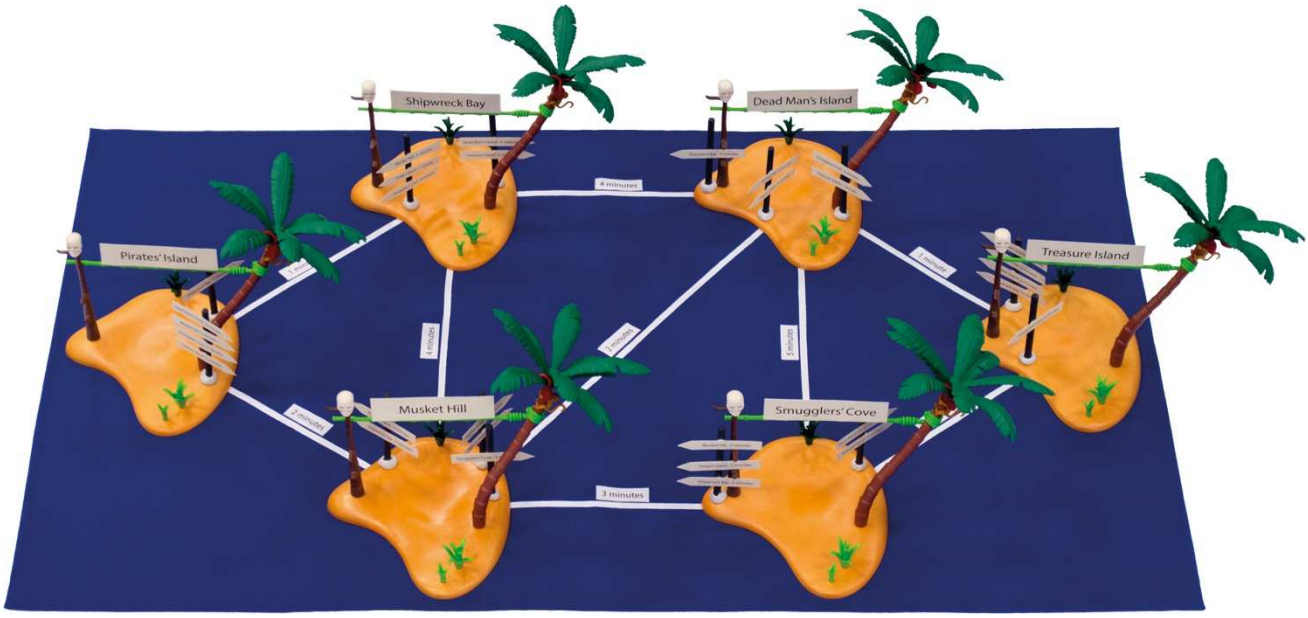

Fig. 1. Physical Concrete (PC) Representation

and abstract referents [37]. In a between-groups pre-test/post-test design, participants were assigned to one of three groups: two-step fading (concrete > concrete > abstract), three-step fading (concrete > intermediate > abstract), and five-step fading (concrete > concrete/intermediate > intermediate > intermediate/abstract > abstract). Results showed that a three-step Concreteness Fading sequence that explicitly linked (indexed) mutual referents led to higher learning gains than a two-step sequence that did not include explicit linking. The five-step sequence led to the highest learning gains overall but was not significantly different to the three-step group. We concluded that explicit linking provided significant value within a Concreteness Fading sequence but that doing so within a single representation may be sufficient.

III. Learning Environment

A. Overview

For our previous experiment, we piloted three Concreteness Fading learning environments, each of which included a physical manipulative in the concrete stage, as per the TMCF recommendation. Pilots were conducted in the host school, with children aged 9 to 10. The first prototype taught bubble sort using a balance scale manipulative, but the abstract representation (programming code) was deemed too advanced for the age range. The second prototype taught finite-state machines using a pirate-themed treasure hunt, but the abstract representation was intuitive enough that no advantage was conferred by adding a concrete representation. The third and final prototype taught the fundamentals of networks (edge lists) and routing tables using a pirates' island metaphor (see Fig. 1) and was selected for use in the experiment [10].

For the experiment described in this paper, our unchanged pirate's island prototype was captured through photogrammetry to create a closely matched 3D model, which was then presented to learners as a tablet-based augmented reality virtual concrete (VC) representation (see Fig. 2). The intermediate and abstract representations were presented on laminated paper and remained unchanged from the first experiment.

B. Physical and Virtual Concrete Representations

Inspired by CSU, the concrete representations use conceptual metaphor to represent a computer network as a group of islands in the ocean. Each island is inhabited by a friendly pirate who can send messages using a carrier parrot. Parrots are only allowed to fly along pre-determined flight paths, shown as white lines labelled with the required flight time. In the first of two worksheet activities, learners are asked to calculate the total time required for a parrot to fly along a specified route, e.g. Smugglers' Cove to Treasure Island to Dead Man's Island to Shipwreck Bay. The learner begins by placing their parrot on Smugglers' Cove, then moving it along flight paths from island to island while summing the flight times. In the second activity, learners are asked to find the fastest route between two islands, e.g. Smugglers' Cove and Shipwreck Bay. The visualised length of each flight path does not imply the flight time; therefore, it is necessary to consult the direction signs positioned on each island. Learners should read the direction signs on Smugglers' Cove to find the one labelled Shipwreck Bay, identify that the

Fig. 2. Virtual Concrete (VC) Representation

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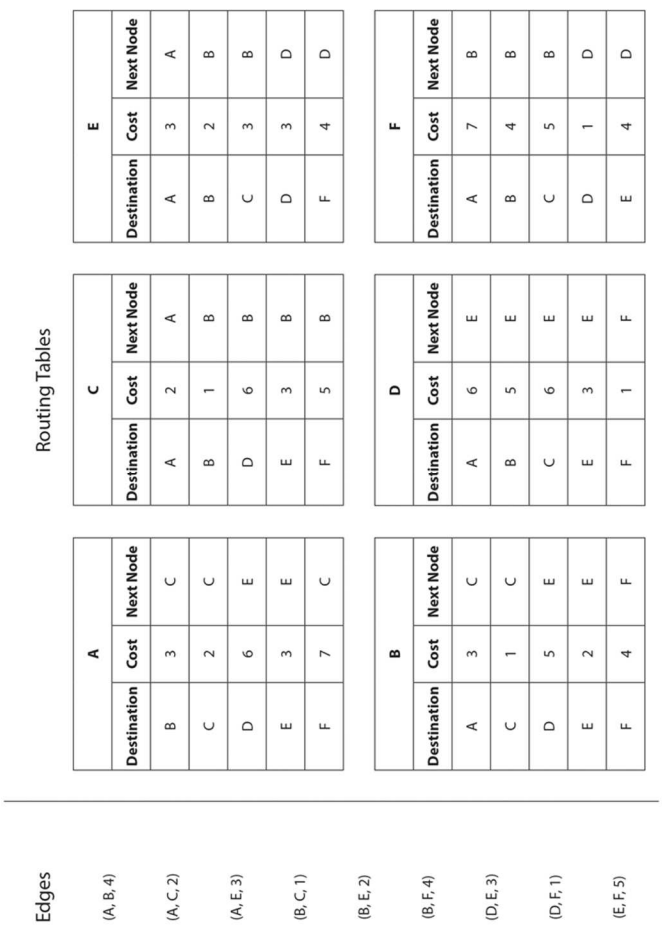

Fig. 3. Abstract Representation

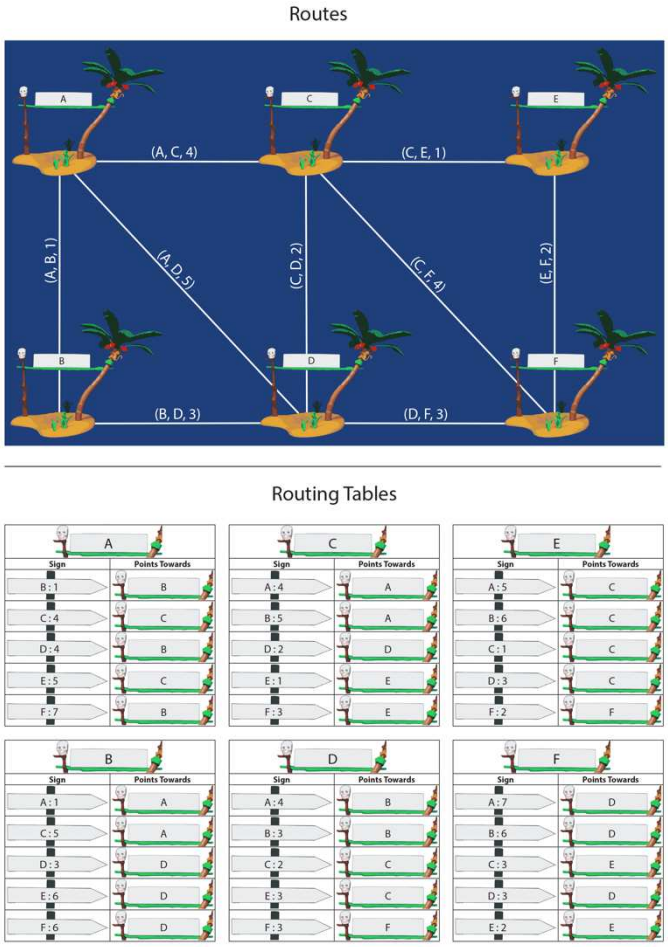

Fig. 4. Intermediate Representation

sign is pointing towards Musket Hill, and then move the parrot along the connecting flight path. This procedure should then be repeated until the destination is reached.

The PC representation was constructed using Playmobil® Pirates Island and parrot toys, wood, cardboard, and cloth. The VC representation was developed in Unity using the Apple ARKit API and installed on a 9.7" Apple iPad Pro, enclosed within a child-friendly rubber case. Through augmented reality, the VC representation appeared to be positioned on the desk at approximately the same dimensions as the PC representation (100cm x 60cm).

For both the PC and VC representations, the researcher provides narration while drawing the learner's attention to the relevant conceptual features: in the PC by pointing and in the VC by positioning the iPad to constrain the view. During the activities, learners should carefully study the representation to find the information needed to complete tasks and, if using the VC, are given control of the iPad to do so. When using the PC representation, learners physically move the parrot from island to island to track their progress along a route. In the VC representation, a virtual parrot hovers above an island and is moved by tapping on-screen at the destination island.

C. *Abstract Representation*

The abstract representation (see Fig. 3) comprises an edge list and routing tables presented without contextualisation or extraneous perceptual detail. Conceptual features are described using abstract language, e.g. flight time is now "cost", and labels are updated, e.g. an edge label of "4 minutes" is now "(A, B, 4)". Without visualisation of nodes or the connections between them, learners are required to consult the edge list to evaluate routes. For example, when asked to calculate the total cost of a specified route, e.g., from C to A to E to D, learners should find each edge, e.g. (C, A, 2), within the edge list and sum their costs. To follow the lowest-cost route across the network, learners are required to consult the routing tables. For example, if asked to travel from C to D, learners should find the routing table for node C, read the "destination" column to find the row for D, and then move to the "next node", i.e. node B. This procedure should be repeated until the destination is reached.

D. *Intermediate Representation*

The intermediate representation (see Fig. 4) was designed to explicitly link the mutual referents between the concrete and abstract representations. Features are presented as iconic forms of their concrete referents but described using abstract language. For example, islands and flight paths are displayed visually but described as nodes and edges, and their labels are presented in

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abstract form, e.g. the edge label (A, C, 4). Iconic forms of the direction signs are displayed in a table format, such that the information should be read from left to right: destination, cost, and next node, as in the abstract representation. The procedure for evaluating routes remains unchanged from the concrete representation, with the minor update that the parrot is replaced with a generic plastic counter. The procedure for following the lowest-cost route is similar to that of the abstract representation. For example, if asked to travel from F to A, learners should find the routing table for node F, read the "sign" column to find the direction sign labelled with A, then move to whichever node the sign "points towards" i.e. node D, and then repeat until reaching the destination.

IV. Experiment

A. Design

This experiment used a between-groups design, with the physicality of the concrete representation as the independent variable. Two groups were compared: physical concrete (PC) and virtual concrete (VC), differing only in the modality of the first stage of a concreteness fading progression (see Table 1). The intermediate and abstract representations were delivered on paper and were identical for all participants. The first dependent variable, learning gain, was calculated as the difference between pre-test and post-test scores. The second dependent variable, changes in attitude towards computing, was calculated as the difference in pre-survey and post-survey scores. After data collection had concluded, participants' mean scores from a recent Cognitive Abilities Test (CAT) administered by the school were used as a covariate in an ANCOVA analysis of the learning gains. (The CAT is a standardised measure of reasoning across verbal, non-verbal, quantitative and spatial dimensions, popular in UK schools at primary and secondary levels.)

	Learning Stage 1	Learning Stage 2	Learning Stage 3
PC	Physical Concrete	Intermediate	Abstract
VC	Virtual Concrete	Intermediate	Abstract

Table 1. Experimental Groups

B. Participants and Settings

Ethical approval for this study was obtained from the relevant University of Sussex Research Ethics Committee (SCITEC C-REC). All pupils in year five (approximately 100 children aged 9-10, across three classes) of a primary school in the South-East of England were invited to participate. The informed consent procedure comprised written parental permission for all participants to take part in the tests and learning activities and gave researchers access to the CAT scores. All sessions took place during normal school hours. The pre-test and pre-survey were completed in the participants' classrooms. The learning activities, post-test, and post-survey were completed in a nearby corridor workspace. The final sample size was 48, comprising 28 females and 20 males, aged between nine and ten years (M=9.22, SD=0.32) with a mean CAT score of 109.75 (SD = 14.58, X(1) = 61, X(n) = 137). All participants were randomly assigned to groups, with characteristics shown in Table 2.

	Physical Concrete	Virtual Concrete
n	25	23
Females	15	13
Males	10	10
CAT M	109.2	110.4
CAT SD	16.1	13.1

Table 2. Group Characteristics

C. Materials

1) Learning Stages

Each of the three stages of learning (see Table 1) comprised four substages: Narration 1 > Activity 1 > Narration 2 > Activity 2. Narration scripts and activity worksheets were closely matched across stages, i.e. participants effectively received the same lesson three times consecutively, differing only in their position on the concrete-to-abstract spectrum. In narration 1, participants were introduced to the new network representation, focusing on nodes, edges and routes. In Activity 1, the worksheet described a specific six-hop route across the network, and participants were asked to calculate the total cost of the route. Narration 2 focused on routing tables, with the researcher demonstrating that fewer hops did not imply a lower-cost route. In Activity 2, participants were asked to use the routing tables to now find the lowest-cost route between the same source and destination as in Activity 1.

2) Pre- and Post-Test

To measure learning gain, all participants completed pre- and post-learning near-transfer tests (see Fig. 5). Two versions of the test were developed (pre-test and post-test), differing only in the names of routers and ordering of features. The test representation was perceptually similar to the abstract learning representation but increased complexity from six to nine nodes and contextualised the network as a "fictional example of how a computer programme might represent the data lines and routing tables that make up the internet". Nodes were described as routers, edges as data lines, etc. Using this representation, participants answered eight multiple-choice questions, for example, "How long does it take for data to travel between Phoenix and Houston directly?" and "What is the fastest that data could be sent from Boston to Miami?". To correctly answer each question, participants would first need to identify whether it referred to the edge list or routing tables (usually indicated by "directly" or "fastest"), then interpret the representation and search for the solution.

3) Pre- and Post-Survey

To measure changes in attitudes to computing, all participants completed pre- and post-learning surveys comprising five statements with agreement recorded on a five-point Likert scale: 1) I like computing; 2) I am good at computing; 3) I like the challenge of computing; 4) Computing is fun; 5) I want to find out more about computing. Statements were selected from a wider range previously used in the evaluation of a game-making project [38].

D. Procedure

The experiment ran from November 2018 to January 2019 and was conducted with three classes consecutively. Each

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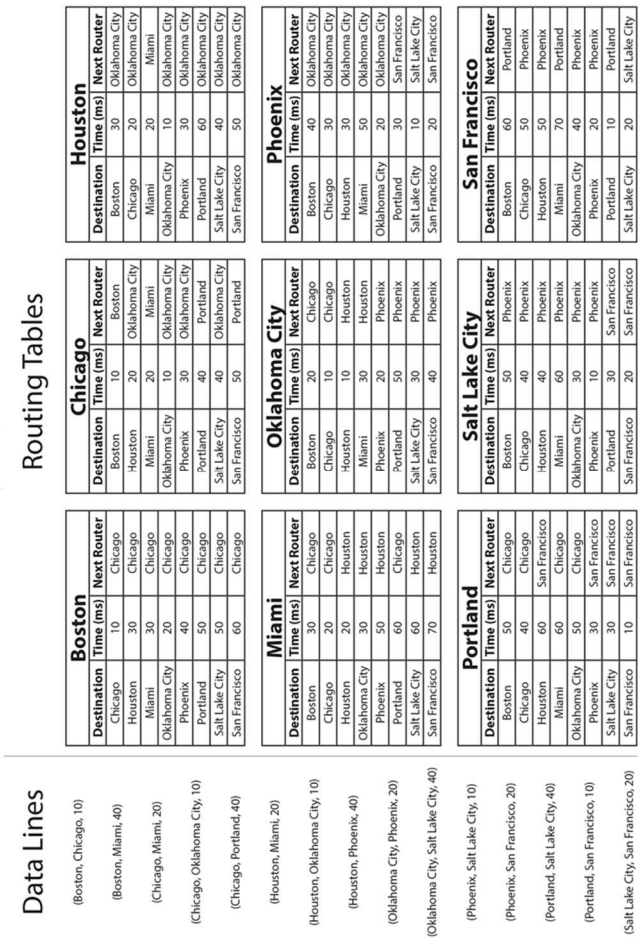

Fig. 5. Pre/Post-Test Representation

participant completed two sessions: the collectively administered pre-survey and pre-test session (S1) and, later, the individually administered learning, post-survey, and post-test session (S2). Three S2 sessions were run each day, alternating daily between VC-PC-VC and PC-VC-PC to ensure matching between groups for S2 start time and duration between S1 and S2, with the latter resulting in a mean of 15.13 days (SD = 13.71, X(1) = 4, X(n) = 46).

The S1 sessions lasted approximately 15 minutes. After an introduction, the pre-survey was distributed to the participants, completed, and collected. The pre-test was then distributed to the participants, face-down, alternating test versions such that no participant was seated next to another with the same version of the pre-test. Participants were asked to turn over their introductory page while the researcher read aloud from it. Participants were then asked to turn over the remaining pages and given seven minutes to complete the multiple-choice worksheet. Finally, participants were asked to put their pencils down, and the pre-tests were collected.

The S2 sessions lasted approximately 30 minutes. Participants were first given an overview of the session and asked for verbal assent to continue, with all agreeing to do so. The procedure for each of the three learning stages was the same. The researcher began by revealing the conceptual representation to the participant and then introduced edges by narration while pointing at the key features, either on-screen (VC) or directly at the model (PC). Next, the researcher revealed the worksheet and completed activity A while narrating their actions, with participants then asked to complete activity B alone. This two-stage process was then repeated to introduce routing tables. It was planned that if a participant were to query a point during narration or provide an incorrect answer to an activity, the researcher would repeat the relevant portion of the script a maximum of two times before moving on. However, no participant needed more than one repetition. After finishing the learning stages, the post-survey and post-test were completed as in the procedure for S1 described above.

V. Results

Table 3 shows participants' scores on the pre-test and post-test for the entire sample and by gender. Independent samples t-tests showed gender differences were not statistically significant on the pre-test (M=0.093, 95% CI [-0.698, 0.884], t(46)=0.236, p=0.814) or the post-test (M=0.729, 95% CI [-0.044, 1.501], t(46)=1.898, p=0.064).

	Pre-test			Post-test		
	Sample	Females	Males	Sample	Females	Males
M	1.35	1.39	1.30	3.13	2.82	3.55
SD	1.33	0.99	1.72	1.35	1.22	1.43

Table 3. Mean and Standard Deviation of Pre-Test and Post-Test Scores (Maximum Test Score = 8).

Table 4 shows participants' learning gains by group and by group*gender. A two-way ANCOVA was run to control for pre-test scores and CAT scores, with covariates evaluated at the following values: CAT score = 109.75 and pre-test score = 1.35. No statistically significant effect was found for either the simple main effect of physicality (F(1,42)=0.093, p=0.762, partial η2=0.002) or the interaction effect of physicality and gender (F(1,42)=3.250, p=0.079, partial η2=0.072), on learning gains.

	Physical Concrete			Virtual Concrete		
	Group	Females	Males	Group	Females	Males
M	1.68	1.13	2.50	1.87	1.77	2.00
SD	1.97	1.69	2.17	1.10	1.30	0.82
Madj	1.89	1.26	2.53	1.78	1.80	1.76
SE	0.25	0.32	0.39	0.26	0.34	0.39

Table 4. Mean, Standard Deviation, ANCOVA Adjusted Mean (Madj), and Standard Error of Learning Gains, by Group and by Group*Gender.

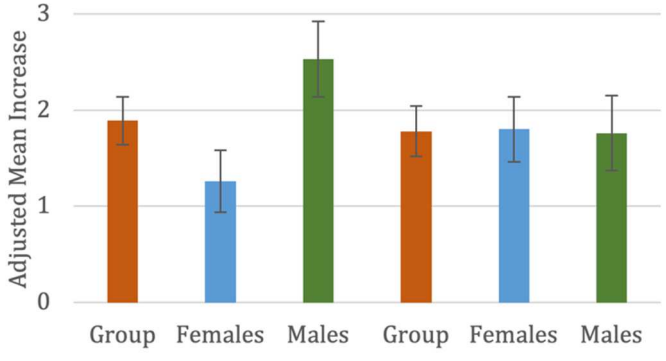

Fig. 6. ANCOVA Adjusted Mean Learning Gains, by Group and by Group*Gender. Error Bars represent Standard Error.

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For analysis of attitudinal change, one female participant in the VC group was removed from the sample due to a misplaced pre-survey and, therefore, N=47 in this context. Table 5 shows participants' scores on the pre-survey and post-survey for the entire sample and by gender. Independent samples t-tests showed gender differences were not statistically significant on the pre-survey (M=0.372, 95% CI [-0.998, 1.742], t(45)=0.547, p=0.587) or the post-survey (M=0.200, 95% CI [-1.031, 1.431], t(45)=0.327, p=0.745).

	Pre-Survey			Post-Survey		
	Sample	**Females**	**Males**	**Sample**	**Females**	**Males**
M	21.94	21.78	22.15	22.91	23.00	22.80
SD	2.29	2.10	2.56	2.05	1.90	2.29

Table 5. Mean and Standard Deviation of Pre-Survey and Post-Survey Scores (Maximum Survey Score = 25).

Table 6 shows participants' attitudinal change by group and by group*gender. A two-way ANCOVA was run to control for pre-survey scores, with the covariate evaluated at the following value: pre-survey score = 21.94. No statistically significant effect was found for either the simple main effect of physicality ($F(1,42)=0.397$, $p=0.532$, partial $\eta 2=0.009$) or the interaction effect of physicality and gender ($F(1,42)<0.000$, $p=0.997$, partial $\eta 2<0.000$), on attitudinal change.

	Physical Concrete			Virtual Concrete		
	Group	**Females**	**Males**	**Group**	**Females**	**Males**
M	0.96	1.27	0.50	1.00	1.17	0.80
(SD)	1.88	1.67	2.17	1.63	1.90	1.32
Madj	1.09	1.29	0.88	0.79	0.99	0.59
(SE)	0.32	0.40	0.50	0.34	0.45	0.49

Table 6. Mean, Standard Deviation, ANCOVA Adjusted Mean (Madj), and Standard Error of Attitudinal Change, by Group and by Group*Gender.

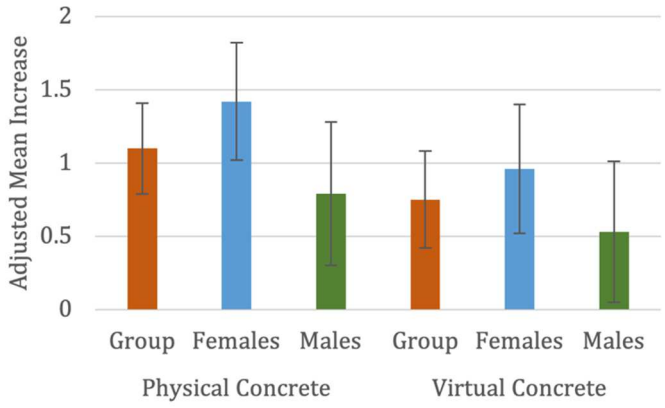

Fig. 7. ANCOVA Adjusted Mean Attitudinal Change, by Group and by Group*Gender. Error Bars represent Standard Error.

VI. Discussion

Physicality made no significant difference to between-group learning gains, suggesting that these particular Concreteness Fading learning materials can be implemented in the classroom as effectively with augmented reality as with physical manipulatives. When examining learning gains by group and gender, a statistically significant interaction effect was not found; however, in the PC group, males scored noticeably higher than females. In the VC group, females scored higher than males, but the difference was negligible. There is little evidence of gendered differences within the existing research comparing PCs and VCs outside of the Concreteness Fading context, and therefore, this result was unexpected. In our previous experiment [10], a trend of males scoring higher than females on learning gains emerged across all groups without reaching statistical significance. However, the difference between male and female learning gains was smallest within a close equivalent of the PC group, so there is some doubt as to the validity of this current finding. The reversal of this trend in the VC group needs replication and further investigation.

The comparison of the virtual and physical representations described in this paper was undertaken for a number of reasons. At the broadest level, it fits within our overall research objective of understanding the potential benefits of the Concreteness Fading approach when applied to computer science concepts (see [10] and [37]). More specifically, the study was conceived in response to Fyfe and Nathan's [11] call to solidify the place of "concreteness fading" as an instructional theory by investigating six hypotheses, in this case, the hypothesis that "a concreteness fading progression that includes a physical manipulative in the first stage will be more effective than one that does not". Fyfe and Nathan [11] further stated that to "truly test this hypothesis, future research should compare groups who each engage with three distinctive representations that become more idealised, but only one group begins with a physical model." This motivated our research question of whether a virtual "manipulative" could potentially be equally as effective as an actual physical manipulative.

Above and beyond furthering our knowledge of the required properties for effective concreteness fading, testing this hypothesis has a number of important practical implications for the use of a concreteness fading approach in the classroom. Firstly, if there is a significant difference between groups who engage with a physical manipulative and groups who engage with a non-physical representation at the same level of abstraction (i.e. concrete), then there are, at the very least, practical resource implications. Classrooms must either have a set of manipulatives available for each child or, if this is not feasible, must limit pupil access to the materials required for this first stage of their learning. However, if the results show no significant difference between groups (as in the case of the current study), then this provides support for the development of a technology-enhanced learning environment that incorporates all three stages using a single (digital) modality. Not only would this have significant positive practical implications, but it also potentially has important theoretical and empirical implications.

Existing research suggests that students have difficulty in moving between representations [6] and that this switch requires significant cognitive overhead. If we want to avoid the issue of switching between representations and the cognitive overhead that this entails, then a potential approach would be to use the same media for all three stages in such a way that more concrete information could be faded out from the representation in place, while more abstract information is integrated. The design advantages of virtual concrete materials have been previously summarised by Moyer-Packenham et al. [15]. One of these advantages may be in the ability to design virtual learning environments that more effectively index concrete and abstract referents. Again, knowing that there is no significant difference

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between the physical and virtual manipulatives in this instance provides more empirical and theoretical support for the development of a technology-enhanced learning environment that would allow students to remain within a single environment, with the move from concrete to abstract happening in situ.

The many mixed results in comparing physical and virtual representations [15], including this one, raise a number of issues. Comparing the educational effectiveness of virtual and physical representations is a special case of comparing any two representations. In such comparisons, various factors need to be considered at a greater level of granularity than just the modalities "physical" or "virtual". These factors include:

1. The **nature of the concepts to be learned**: their complexity, the number of factors they have, and the degree to which they involve change or interactions with other concepts.
2. The **nature of the representation** of the concept: not just its modality but its degree of fidelity, its salience with respect to the concept, and the boundary conditions on its representativeness.
3. The nature of the **learner's interaction with the representation and its affordance**: is the representation passive (e.g. a diagram in a book or a sentence on a page) or reactive (e.g. a simulation on a screen where the parameters can be adjusted by the learner)?
4. If it is reactive, **how may the learner manipulate it** (e.g. pressing a virtual button on a computer screen or moving a lever on a physical model)? Is the nature of the learner's physical manipulation "faithful" to the concept (e.g. in learning about equality, placing and taking off weights on a physical balance is faithful, but dragging and dropping an image of a weight onto an image of a balance is not faithful as the crucial issue of the "weightiness" of the weights is not experienced by the learner in the virtual representation). Finally, how does the representation react and change as a result of manipulation and are these changes and reactions faithful to the conceptual changes that they represent?
5. The **context within which the representation is used**, including the temporal and spatial relationships to other representations (see [32]).

In this experiment, the physical representation was passive and manipulable only in the sense of tracing routes by repositioning a toy parrot. The virtual representation faithfully retained this passivity, though it introduced a different kind of manipulability of the whole tablet to see different parts of the representation in more detail. To a large extent, the virtual and physical representations were similar across all five dimensions above. Had either of the representations been reactive and potentially afforded different kinds of manipulability, then there might well have been differences in learning outcomes, with either the physical or the virtual doing better in terms of learning gains depending on the fidelity of the manipulation to the concepts in question (see point 4, above).

In summary, as the VC representation required some degree of physical interaction, i.e. moving the iPad to view the relevant conceptual elements and touching the screen to complete tasks, it cannot be inferred that physicality was of zero effect in this experiment. Therefore, further work would be required to establish whether VCs can be implemented in other forms (in the context of the points made above) within Concreteness Fading without detrimental effects on learning or attitudes towards computing.

Finally, the learning environment described in this paper focuses on declarative tasks, whilst Johnson-Glenberg et al. [30] only found benefits for physicality when learners were carrying out generative tasks. Other computing education activities (most notably programming) are likely to be considered generative tasks, and future research should investigate whether this distinction and any potential benefits of physicality hold elsewhere in computing.

VII. Conclusion

This paper presented a study investigating the effect of the physicality of the concrete representation in a TMCF progression. Two groups were compared: physical concrete and virtual concrete (implemented in an augmented reality tablet application). The results showed no statistically significant difference between the two groups, contrary to the guidelines of the TMCF. We have discussed the implications of the lack of evidence regarding the benefit of physicality and the potential practical and pedagogical benefits of a virtual environment. We have also discussed these findings in relation to the wider literature and noted that there are additional factors beyond "physical" and "virtual" which likely play an important role and would need to be investigated further to understand the consistently mixed findings in this area.

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