



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Identifying embodied metaphors for computing education

Citation for published version:

Manches, A, McKenna, P, Rajendran, G & Robertson, J 2020, 'Identifying embodied metaphors for computing education', *Computers in Human Behavior*, vol. 105, 105859, pp. 1-11.
<https://doi.org/10.1016/j.chb.2018.12.037>

Digital Object Identifier (DOI):

[10.1016/j.chb.2018.12.037](https://doi.org/10.1016/j.chb.2018.12.037)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Computers in Human Behavior

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Identifying Embodied Metaphors for Computing Education

Abstract

Computing education is increasing in global importance, with calls for greater understanding of conceptual development that can inform pedagogy. Here, we report a study investigating elementary computing concepts through the lens of Embodied Cognition. Sixteen students (9 female) studying university-level computing were asked to explain their understanding of computing concepts (without materials) in individually video-recorded sessions. We analysed the gestures generated for three elementary concepts: algorithms, loops, and conditional statements. In total, 368 representational gestures were identified across 48 (16×3) explanations, thereby providing evidence that offline thinking in this domain is embodied. Our analysis of representational gestures showed that participants drew upon two overarching embodied metaphors in their explanations: 1) Computing Constructs as Physical Objects, in which participants simulated manipulating physical objects (e.g., pinching) when referring to range of computing constructs, and 2) Computing Processes as Motion along a Path, whereby participants moved their hands along one of three body-based axes when referring to temporal sequences. We contrast our findings to similar research in mathematics and discuss implications for computing pedagogy – namely the role of gesture in the classroom and technologies that can exploit embodied metaphors.

Keywords

Embodied Cognition; Gesture; Metaphor; Computing Education; Computational Thinking; Representation

Introduction

“An algorithm? Asked Ann. She had never heard of an algorithm for quests. Hope flowed through her. She could handle algorithms. “It’s simple” started Sir Galwin. “If you have one or more leads, you follow the best one. Otherwise, if you don’t have any leads, you travel to where you can find more information. Break any ties by flipping a coin.”

(Kubica, 2012, p.17)

Kubica (2012) argues that computing concepts – from Algorithms to Depth-First Searches – are illuminated through metaphorical storytelling. While the use of metaphors or analogies to teach students computing concepts is commonplace, it is not usually clear how these mappings are derived, i.e., whether they are informed by any theoretical understanding of conceptual development in the domain. Increasingly, there have been calls to improve computing education (Brown, Sentance, Crick, & Humphreys, 2014; Wing, 2008) that have led to curricula change in several countries. However, concerns have been raised about the theoretical evidence base for the understanding of learning in this domain. Grover and Pea (2013) make the case for Learning Sciences research to offer such an evidence base, especially from the field of Embodied Cognition. As well as addressing fundamental questions concerning the nature of thinking, Embodied Cognition has also been applied in the design and implementation of learning environments, notably in the domain of mathematics (Eisenberg, 2009). Given the role of metaphor in Embodied Cognition perspectives (Lakoff & Johnson, 1980; Núñez & Lakoff, 2000), this field has strong implications for computing, which, as exemplified above, has historically drawn upon metaphor and analogy in its teaching (e.g., Hui & Umar, 2010; Pollard & Duvall, 2006). Despite this, there has been little empirical research adopting the theoretical lens of Embodied Cognition to promote our understanding of the development of computing concepts, or approaches that draw upon this field to inform computing education.

In this paper, we first present theoretical literature on Embodied Cognition, conceptual metaphor and gesture research and subsequently relate this work to the domain of computing. We then report our method, adopted from gesture research, and results, where we present original empirical findings for the embodied nature of computing concepts through the analysis of gestures generated by individuals explaining three core computing concepts. Furthermore, we identify representational patterns from these gestures thereby demonstrating the potential of this methodological approach to provide a deeper understanding of the nature of thinking in this educational domain. Finally, we consider the implications of this paper for future work and interventions, as well as draw attention to methodological limitations.

Consequently, the core contribution of our work is to help reveal the conceptual foundations of basic computing concepts through a novel and rigorous research approach. Our findings compliment work aiming to identify the cognitive foundations in computer science, such as Roman-Gonzalez, Perez-Gonzalez and Jimenez-Fernandez (2017) who provide evidence for computational thinking, but via psychometric measurements. We draw upon the findings to describe how this methodological approach may inform pedagogy and the design and implementation of learning

environments, where instruction needs to be grounded in deep conceptual understanding for science concepts and education. Here, we share the view with Niebert, Marsch, and Treagust (2012) that ‘understanding needs embodiment’.

1. Literature Review

1.1 Embodied Cognition, Conceptual Metaphors and Gesture Research

1.1.1 Embodied Cognition

Until the 1980s, dominant theories of cognition viewed knowledge as residing in a semantic memory system separate from the brain’s modal systems for perception (e.g., vision, audition), action (e.g., movement, proprioception), and introspection (e.g., mental states, affect) (see Barsalou, 2008). So, cognitive science typically assumed a view of the mind as an abstract information processing system, in which our sensory and motor (sensorimotoric) systems served a peripheral role conveying information to and from a central cognitive processor (the brain) where high level abstract thinking took place. Various theoretical perspectives then emerged challenging this position. The work of Ed Hutchins,(1995), for example, argued that cognition should be considered as distributed across objects, individuals, artefacts, and tools in the environment. Related to Hutchins’ work is Scaife and Rogers’ (1996) proposal of External Cognition which emerged from their work examining the role of graphical representations. The authors define external cognition as a complex iterative relationship between internal and external representations involved in problem solving. Whilst Distributed and External Cognition theories drew attention to our capacity to externalise, or offload, thinking; theoretical work also started to recognise how cognitive processes are not confined to the brain but are deeply rooted in the body’s interaction with the world (Lakoff & Johnson, 1999; Varela, Thompson, & Rosch, 2017): cognition is embodied.

According to Wilson (2002), Embodied Cognition is an umbrella term capturing various claims, of which she identifies at least six. Five of these refer to the way we use the environment (and others) as a dynamic resource to reduce ‘online’ cognitive demands – as articulated in other distributed, social and external cognition theories. Wilson contrasts these ‘online’ cognition claims with a more controversial sixth: that our thinking in the absence of ‘relevant stimuli’ – our ‘offline thinking’ - is encoded modally rather than amodally (Barsalou, 1999), and we draw upon these modal, or ‘embodied’, resources to think, reason and communicate different ideas through conceptual mappings. One process in which we achieve such conceptual mapping is through *conceptual metaphors*, which Núñez (2000, p. 5) describes as the “cognitive mechanism by which the abstract is comprehended in terms of the concrete”.

1.1.2 Conceptual Metaphors

Conceptual Metaphor theory emerged from the field of cognitive linguistics, with the proposal that from repeated embodied experiences with the world, generalised ‘image schemas’ emerge that we map metaphorically to abstract concepts (Lakoff & Johnson, 1980). For example, our conceptualisation of *time* is grounded upon experiences of linear motion in space; for many cultures (not all), the future is seen as something in front of us, and the past behind (Núñez & Sweetser, 2006).

Similar to analogies (see Gentner, 1983), conceptual metaphors involve mappings between a source domain (e.g., movement) and target domain (e.g., time). The key difference is directionality i.e., the target domain is understood, often unconsciously, in terms of relations that hold in the source domain; whereas the source domain is rooted in everyday sensorimotoric experience. Conceptual Metaphor theory, therefore, offers an explanation for our ability to think and reason about abstract concepts, and despite critiques of the theory (see Kövecses, 2008), has provided a valuable theoretical framework for examining the conceptual underpinnings of abstract concepts, notably in science (e.g., energy transfer (Close & Scherr, 2015); thermodynamics (Brookes & Etkina, 2015; Jeppsson, Haglund, & Amin, 2015)) and mathematics (Murphy, 2009; Núñez & Lakoff, 2000; Stacey, Helme, & Steinle, 2001).

Much of the empirical support for conceptual metaphors comes from analysis of language, for example, in mathematics, language such as “take away” and “break” or “count up” and “next” may indicate how we conceptualise numbers as collections of objects or as points along a path (see Núñez & Lakoff, 2000). However, when we communicate such concepts, we do not just use words; we often gesture. And increasing work suggests that these gestures provide another window into the conceptual metaphors underpinning abstract concepts, thereby supporting claims that cognition is embodied.

1.1.3 Gestures

During problem-solving or explaining, we move our hands, even when there is no listener present (e.g., while on the telephone) or even when both the listener and the speaker are blind (Iverson & Goldin-Meadow, 1997). Such work suggests that the primary function of gestures is to support the speaker; although gestures do also support the listener’s comprehension. According to McNeill (1992, p. 37), gestures refer to “idiosyncratic spontaneous movement[s] of the hands and arms accompanying speech”. Whilst speech is more analytic, gestures are more global and image-based, providing a unique lens to examine meaning (Parrill & Sweetser, 2004).

Gestures support cognitive activity by enabling the speaker to externalise dynamic visual imagery, and in doing so, they provide additional information about the speaker's conceptualisation. Gestures are frequently used by both children and teachers (Alibali & Nathan, 2007; Flevares & Perry, 2001) and so provide a rich source of data with which to examine cognition, as well as influence learning. Indeed, the last twenty years has created a substantial body of literature documenting the potential of gesture to support learning (Goldin-Meadow, 2009). Teachers are able to use children's gestures to assess learning (Kelly, Singer, Hicks, & Goldin-Meadow, 2002) and identify readiness to learn new concepts (Pine, Lufkin, & Messer, 2004). It is also possible to support learning directly by encouraging children to gesture, possibly because this can reduce cognitive load in tasks (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001), make implicit knowledge explicit (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007) or provide new action representations that children can later draw upon (Goldin-Meadow, Cook, & Mitchell, 2009). Furthermore, teachers' gestures can support learning (Valenzeno, Alibali, & Klatzky, 2003). Whilst teachers tend to gesture spontaneously, work has shown the value of training teachers to use gestures (Hostetter, Bieda, Alibali, Nathan, & Knuth, 2006).

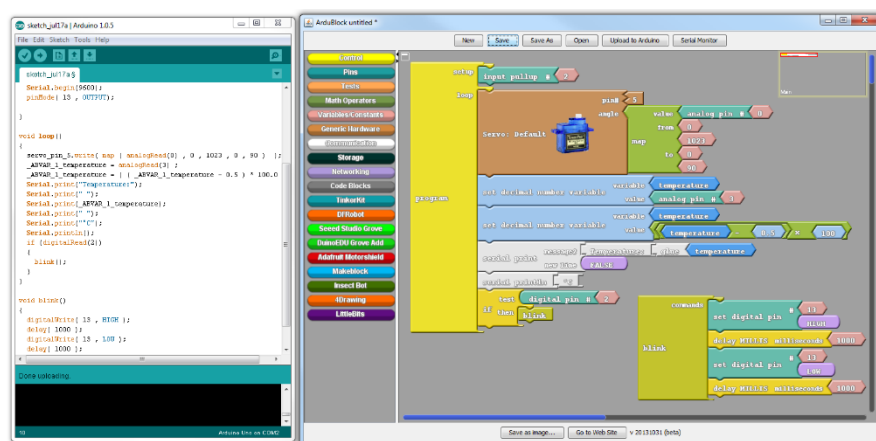
According to Hostetter and Alibali (2008), gestures emerge from perceptual and motor simulations that underlie embodied language and mental imagery, i.e., gestures are simulated actions. The authors focus on representational gestures, i.e., those gestures that represent the content of speech by pointing to a referent (deictic gestures), those depicting a referent or its trajectory (iconic gestures), or those depicting a concrete referent or its trajectory for an abstract idea (metaphoric gestures). The authors contend that metaphoric gestures arise from perceptual and motor simulations of spatial image schemas on which conceptual metaphors are based. Therefore, analysing these gestures is a way to examine conceptual metaphors empirically (Amin, Jeppsson, & Haglund, 2015). Edwards (2009) for example, drew upon Conceptual Metaphor theory to analyse the gestures generated by student teachers when asked to explain their understanding of fractions. In the study, 251 gestures were generated by the 12 participants (student teachers), of which 81 referred to fractions. From her data, Edwards offers a simple topology distinguishing gestures that draw upon experiences with tangible objects (e.g., cutting objects into equal partitions) and those that simulate writing of mathematical procedures or spatial locations of symbols.

Given the potential of examining metaphorical gestures to develop our understanding of thinking in abstract domains such as mathematics and science, it is necessary to ask whether such gestures are evident when individuals communicate their thinking in the domain of computing. Yet, whilst there is anecdotal evidence to suggest so (e.g.,

online video explanations of computing concepts¹) our review of the literature did not reveal relevant empirical work; although we are not the first to identify the significance of embodiment for computing education (e.g., Landy, Trninic, Soylu, Kehoe, & Fishwick, 2014).

1.2 Embodied Cognition and Computing concepts

Computing literature emphasizes the abstract nature of thinking in this domain. For example, Kramer (2007, p. 38) states that ‘abstraction’ is key to computing, both the “ability to perform abstract thinking and to exhibit abstraction skills”. According to Wing (2008, p.3717), “the essence of computational thinking is abstraction. In computing, we abstract notions beyond the physical dimensions of time and space”. From this perspective, the role of metaphors and analogies is simply pedagogical – to provide ways (e.g., visual imagery) to help students to access abstract notions. For example, many programming environments (e.g., Figure 1) have adopted block building as a visual metaphor to help children understand the syntactic nature of code. There are even physical activities that have been developed that aim to engage children with body-based analogies of computing concepts, such as the work of Computer Science Unplugged (Bell, Lambert, & Marghitu, 2012), which provides a range of non-computer based activities and games such as running around lines in a playground to explore the concept of sorting networks. According to Cortina (2015), such activities are effective because “by being physically part of the solution to a problem as it is being solved, kids learn from observations and experiences”. However, no clear theoretical framework is provided for why certain body-based experiences may develop thinking, beyond motivation.



¹ E.g., Computing at School explanation videos <https://www.youtube.com/watch?v=VowsYScyWNg&t=33s>

Fig. 1. Blocks representing construction of code (Arduino)

Embodiment offers a different perspective on metaphors in computing cognition. Rather than just making abstract concepts more tractable, metaphors may be important in the way we conceptualise certain computing concepts. That is, conceptual metaphors might be the very mechanisms that we use to make sense of, reason about, and communicate computing concepts (similar to claims in mathematical cognition). If embodied metaphors do underpin the way individuals conceptualise certain computing notions, then these metaphors may be evident when people are asked to communicate their thinking. Such evidence would have important implications for computing education.

1.3 Embodied Metaphors and Instruction

According to Amin (2015), investigating conceptual metaphors has the following implications for education:

- characterizing scientist and learner conceptions and identifying obstacles to learning;
- understanding the process of conceptual change; and
- suggesting productive pedagogical strategies.

With respect to pedagogical strategies, an embodied approach suggests the use of particular gestures to support learning (Goldin-Meadow, 2015), the use of instructional materials (Pouw, van Gog, & Paas, 2014), or the development of learning designs leveraging emerging technologies (e.g., gesture recognition devices, tangible technologies) that detect and dynamically link body-based actions to digital representations (Abrahamson, 2009; Lindgren et al., 2016). While research has informed other STEM subjects (notably mathematics and science), we propose that this field can contribute to computing education. This research is especially timely in light of recent calls for increased research into computational practice and perspectives in formal education (Lye & Koh, 2014).

Here, we investigate the role of Embodied Cognition in computing concepts by examining if, and how, individuals generate representational gestures when explaining computing concepts – and if so, how these gestures provide a window into underlying conceptual metaphors. As the first study we are aware of examining gestures in computing science, this study is exploratory, with our overarching research question being: *what types of embodied metaphors, if any, do individuals generate when explaining elementary computing concepts?*

2. Methodology

2.1 Participants

This study adhered to British Psychological Society ethical guidelines and ethical clearance was provided through the University's ethical committee. With the intention of examining spontaneous, rather than more purposeful and rehearsed, gestures, we recruited university students who were familiar with elementary computing concepts (so were able to communicate effectively); yet were unlikely to have rehearsed verbal explanations of concepts. Participants were 16 computer science students aged 18 to 37 years ($M=23.1$, $SD=5.1$) from three universities in the Edinburgh area of the UK. Data from all subjects were analysed; although there was a video recording error for one explanation. This sample size is comparable in similar exploratory in-depth gesture analysis work (Cooperrider, Gentner, & Goldin-Meadow, 2016; Edwards, 2009; Flevares & Perry, 2001; Núñez & Marghetis, 2014), and was therefore considered adequate. All students were competent English speakers, although English was not the first language for half of the participants. Students were mainly undergraduates, in the second semester of their first year ($n = 8$), with several in their second year ($n = 3$). Three were master's students and two were doctoral students. Nine participants were female (56%) and all participants were right-handed.

Participants were recruited from lectures, targeted email lists, as well as generic school wide emails, where female participants were particularly encouraged to ensure gender representative data. All participants gave written consent and received a small monetary incentive. Thirteen participants consented to their images being used to illustrate the data.

2.2 Design

The study drew upon the theoretical framework of Embodied Cognition and the methodological tools of cognitive linguistics and gesture research to examine the gestures generated by participants during their verbal explanations. We interpret meaning from individuals' gestures from context (e.g., the structured interview) and corresponding speech (Parrill & Sweetser, 2004).

The study was conducted as an interview where participants were asked to explain their understanding of computer science terms. Although less naturalistic than work in this field capturing everyday interaction (Flevares & Perry, 2001; Nemirovsky, Rasmussen, Sweeney, & Wawro, 2012), this approach echoes comparable work (e.g. Cooperrider et al., 2016; Edwards, 2009) as it provides a means to generate rich data over a short period as well as consistency between participants. Despite limitations of sampling discussed later in the paper, the methodological approach was considered

ideal for addressing the research question, namely, to explore the embodied metaphors that individuals' produce, if any, in their conceptual explanations of computing concepts.

All 16 participants were given the same concepts in the same order (the sample was too small to counterbalance order). Importantly, participants were not given relevant external resources (e.g., physical materials, whiteboard, computer screen) in order to limit the use of context-specific deictic gestures (and actions) directed toward these resources (i.e., online cognitive processing; Wilson, 2002). This contrasts with other studies (e.g., Herbert & Pierce, 2007) where resources provided are likely to have influenced gestures.

2.2.1 *Computing concepts*

Participants were asked to explain the following three elementary computing concepts: *algorithms*, *loops* and *conditional statements*. We selected these concepts by a) examination of the Association for Computing Machinery 2013 guidelines for university computer science curriculum² b) discussions with computing education experts that the concepts were meaningful across ages of computing education (from Primary to Higher Education).

2.3 Procedure and Materials

Participants were interviewed individually by the 2nd author of the paper in a quiet room within each participant's university. Interviews were video recorded using a Panasonic HD video camera mounted on a tripod in the corner of the interview room. At the beginning of the interview, the interviewer briefly explained the purpose of the research in terms of examining experts' understanding of different computing concepts. The focus of gesture in the study was not revealed at this stage (or in any information prior to the study). However, all participants were fully debriefed after taking part.

Participants were interviewed standing because during piloting we found that sitting could sometimes hinder and/or obscure gesturing. Current initiatives across universities encourage less sitting at work, so, arguably standing would seem natural and not influence explanations. No participants said they perceived this as extraordinary when questioned afterwards.

² https://www.acm.org/binaries/content/assets/education/cs2013_web_final.pdf

The interviewer then read out various computing terms and for each asked participants to explain “*as clearly as you can*”. For the first computing term, the interviewer asked: “*Can you explain your understanding of [pause] “Algorithm?”*”. Thereafter, the interviewer simply stated the next term.

The interviewer judged an explanation to be finished when participants gave an explicit cue, either verbally or otherwise (e.g., nod of head). The interviewer limited feedback (beyond general positivity) in order to minimize any influence on the participants’ explanations. Furthermore, the interviewer did not gesture because this may have primed participants’ embodied representations (i.e., led to mirroring). While this may have created a slightly unnatural socio-communicative context, the influence was not obvious. If participants asked for feedback during the interview, such as asking whether they should use an example, the interviewer would reiterate the task by saying “*if you just explain your understanding as clearly as you can*”.

After the participant had finished explaining the final computing concept, the interviewer debriefed the participant about video recording – i.e., the focus was on their use of gesture as well as speech. The interviewer also asked the participants whether they remembered using gestures and, if so, why they think they used gestures. Only one participant stated suspecting the focus was on gesture.

2.4 Measures and Data Analysis

Videos of participants’ explanations were transcribed and analysed using video annotation software (ELAN; Wittenburg, Brugman, Russel, Klassmann, & Sloetjes, 2006) to provide an overview of the proportion of time different individuals gestured for concept explanations. For each explanation, two coders (1st and 2nd author) independently coded all representational gestures, drawing upon spoken language to guide interpretation. A representational gesture was defined as a gesture – handshape or motion trajectory – depicting aspects of their meaning, either literally or metaphorically (Alibali & Nathan, 2011). There was a moderate agreement between coders (Cohen’s Kappa = 0.52), which is line with other studies (e.g., Cienki, 2005). After coding, coders resolved discrepancies, which were mostly about the start and end point of individual gestures within the flow of hand movement.

From the representational gestures identified, the first and second author then worked together to identify patterns across participants of conceptual mappings – mappings between gesture and conceptual entities evident in speech. Although such interpretation is subjective by nature, interpretation evolved from discussion between coders and has

been made explicit in the findings section (see Parrill & Sweetser, 2004). This interpretative process was facilitated by the focused interview approach (i.e., the context constrained what types of concepts were being discussed).

3. Results

3.1 Individuals' use of gesture

3.1.1 Gesturing time

All 16 participants provided a verbal explanation for each concept, and used gesture for at least one of their three explanations; indeed, gestures were used on 43 out of 48 explanations (16 x 3). Table 1 summarises the participants' speech and gestures for each concept. Non-parametric analyses revealed no significant differences in the amount of gesture or speech time between concepts.

Table 1. Descriptive summary of time (secs.) for speech and gesture for each concept

	<u>Speech</u>			<u>Gesture</u>			<u>Gesture/Speech</u>
	Range	Median	Total	Range	Median	Total	%
Algorithm	8-128	22	481	0-62	10	229	48
Loops	12-85	23	491	0-47	15	294	60
Conditional	3-41	15	275	0-28	8	148	54
Overall	42-214	67	1246	7-102	33	671	54

Note. Gesture/Speech refers to the proportion of time participants gestured during speech.

3.1.2 Representational gestures

In total, 368 representational gestures were coded across a total of 48 explanations (16 participants with 3 concept explanations). Table 2 illustrates the number of representational gestures created by each participant for each concept. The total number of gestures for participants ranged from 3 to 76 (Median = 25).

Table 2. Number of representational gestures generated by each participant for each concept

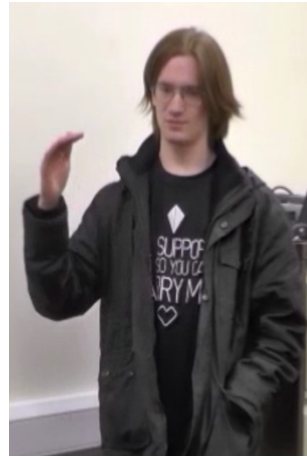
Participant	Algorithm	Loops	Conditional Statement	Total
1	5	3	0	8
2	12	7	11	30
3	0	0	3	3
4	6	7	7	20
5	10	11	11	32
6	13	6	6	25
7	0	22	2	24
8	2	7	5	14
9	43	33	Missing data	76
10	8	12	7	27
11	4	10	0	14
12	3	12	5	20
13	7	8	7	22
14	5	8	11	24
15	6	7	5	18
16	2	4	5	11
Total	126	157	85	368

3.2 Embodied metaphors

During explanations of the concepts: algorithm, loop and conditional statements, the 16 participants created a total of 368 representational gestures used to refer to a range of computing constructs including but not limited to: *data, code, process, input, execution, output, conditions*. For some gestures, there was a direct mapping between the gesture and an external representation, e.g., lines of code on a vertical graphical interface. For example, Participant 8 used her fingers to denote the bracketed boundaries of an IF statement (Figure 2a), or participants pointing in steps from top to bottom while explaining an algorithm (Figure 2b). These gestures might be described as iconic, where the concrete referent is coding script. Yet, such external representations are designed around various metaphors, blurring the distinction between iconic and metaphoric gestures.



(a) P8



(b) P1

Fig. 2. Gestures with iconic mapping to code on screen (a) P8 and (b) P1

P8: “If the statement in the **IF** condition is met”³

P1: “You give **steps**” [RH moves down in 4 steps]

From data across all participants, many gestures appeared to be grounded upon two key image schemas (cognitive structures arising from repeated embodied experiences): the container schema, consisting of three parts: an interior, a boundary and an exterior, and a path-source-goal schema. These two schemas are described by Núñez & Lakoff (2000) as underpinning key concepts in mathematics, and it is perhaps unsurprising they are evident here given the strong domain correspondence between computing and mathematics (Knuth, 1974). These schemas underpin two conceptual metaphors we identified from the data and are used to structure findings.

3.2.1 Computing Constructs As Physical Objects

When explaining concepts, 14 out of 16 participants simulated a grasping or pinching action at least once. Such hand forms are described in work focusing on mathematical concepts (Edwards, 2005; Núñez & Marghetis, 2014).

However, whereas numbers are often represented physically, it is less likely that participants were drawing upon experiences manipulating tangible representations of computing concepts.

³ Bold text indicates creation of gesture; underlined text duration that gesture form is held. LH: Left Hand; RH: Right Hand; BH: Both hands

The form of the hand, and whether one or two hands were used, suggested differences in the perceived size of the imaginary object. This is particularly interesting because physical size has no literal meaning in relation to computing concepts. For example, a two-handed grasp was used by P6 and P8 (Figure 3a) when referring to an *algorithm*. P2 used a similar gesture when referring to *code* (Figure 3b), and again when referring to a *condition*, as did P5. P12 (Figure 3c) used the gesture to refer to a *loop* and P15 used the gesture when referring to a loop as a “*set of tasks*”.



(a) P8

(b) P2

(c) P12

Fig 3. Two-handed grasping gesture (a) P8, (b) P2 and (c) P12)

P8: “An IF Statement is **part of the algorithm that** contains...”

P6: “Use over a large amount of data, in order to sort it, find something or make it more usable”

P12: “...doing something with **anything you put into a loop**”

For some gestures, participants created a grasp hand form with two hands but their hands were cupped upwards and spaced apart suggesting they were holding two separate objects. Two participants used this gesture when referring to *data*, both moving each hand up and down alternatively as if weighing the simulated objects. In a related example, several participants created two cupped hands when discussing *IF statements*, where one hand (the left) simulated holding the *IF* part of a statement and the other (right) holding, or indicating the other part of the statement (Figure 4a; 4b). P6 created a similar cupped hand when saying *IF*, but then used her right hand to represent the condition, which she

referred to as “*Blank*” (Figure 4c). One participant (P10) only used one cupped hand denoting the IF statement. A cupped hand was also used by P8 when referring to a *program* and P7 referring to a “*bug in the program*”.



(a) P14

(b) P13

(c) P6

Fig. 4. Hands holding separate objects (a) P14 (b) P13 and (c) P6

P14: “An **else if** or whatever”

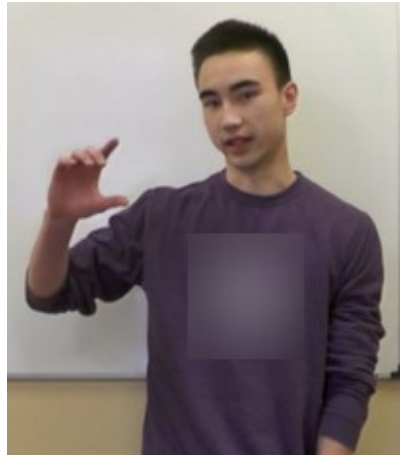
P13: [Gesture created before speech] “if something is true...” ...

P6: “**If blank** / then...”

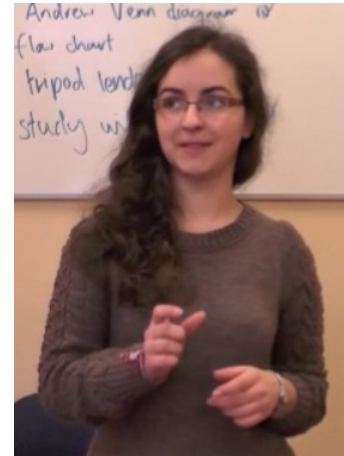
In contrast to a grasping or cupping action, many participants created a pinch in their explanations, as if manipulating a smaller object. This hand form was used when describing verbally a range of constructs including IF statement (P2- Figure 5a), (algorithmic) steps (P1; P4), condition (P4), Loop (P4; P15); True (P4), Command (P8), Section of code (P11- Figure 5b), Bytes of code (P9 – Figure 5c), Else (P14); and Attribute (P16).



(a) P2



(b) P11



(c) P9

Fig. 5. Pinching action (a) P2 (b) P11 and (c) P9

P2: “When you say this is an If statement....”

P11: “Section of code”

P9: “Bytes of code”

As well as hand form, there were gesture movements that presented computing concepts as objects. These gestures would often involve one hand acting as a ‘placeholder’ (Figure 6a) or boundary of an object, and then the other hand arcing into this hand (Figure 6b), or arcing away from this hand. Often there would be associated language around adding or taking away (e.g., Figure 6c).



(a) P13

(b) P14

(c) P16

Fig. 6. Placing or taking away an object (a) P13 (b) P14 and (c) P16

P13: “Extract **some** kind of feature” [Grasping RH arcs away from body]

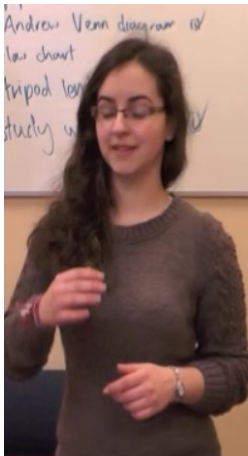
P14: “Whatever’s **inside** the code” [LH swoops down]

P16: “**Set** of instructions” [RH fingers placed inside LH which closes slightly]

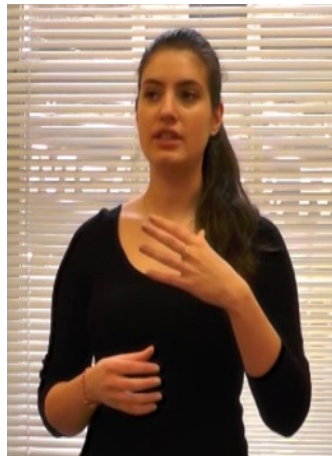
3.2.2 Computing Processes As Motion Along A Path

Longitudinal axis: pathway up to down in front of body

In relation to the body, there are three main axes: longitudinal, transverse, and frontal. Similar to reading text, individuals read and write code from top to bottom on a vertical screen: a longitudinal axis. Therefore, gestures referring to time-based computing processes might move downwards in a longitudinal plane. Indeed, this gesture was observed in several participants (Figures 7a; 7b; 7c) discussing algorithmic steps/instructions, with most marking steps going downwards with a finger or side of the hand (P1, P2, P5, P7, P8, P9 P13, P15).



(a) P9



(b) P8



(c) P13

Fig. 7. Sequential steps down on a longitudinal plane (a) P9 (b) P8 and (c) P13

P9: “What **steps we are following**” [RH moves arcs three points downwards]

P8: “or **set of instructions**” [LH arcs three points downwards]

P13: “instead of having to write, **do A, do A, do A**, in a sequential way” [LH finger arcs three times downwards]

Transversal axis: pathway left to right across the body

Again, similar to text, code is typically written from left to right, which suggest that gestures communicating computational processes might trace a similar transversal axis. Ten participants (P3, P4, P5, P6, P7, P10, P11, P13, P15, P16) created at least one gesture where they moved one or both hands from left to right while describing a process. However, the participants utterances were referring to general processes (e.g., output; ‘executing code’), rather than individual lines of codes. Therefore, this general left to right schema for time based processes is comparable to the same left to right ordering found for concepts such as number (Dehaene, Bossini, & Giraux, 1993).

Participants also showed transversal gestures to communicate processes. For example, gestures involved small left to right arcs when they referred to algorithmic steps. In contrast, several participants created a single horizontal gesture or arc to the right; typically, when referring to a more general resultant process, such as completing instructions (Figure 8a) or achieving “output” (Figure 8b). Interestingly, two participants who created a gesture to the right when discussing a resultant process, used a subsequent arcing gesture back to the left when describing back to a previous step in the process – for example, a failed condition (Figure 8c).



(a) P16



(b) P13



(c) P3

Fig. 8. Left to right transversal gestures communicating time-based processes (a) P16 (b) P13 and (c) P3

P16: “What a computer takes in and **completes** [BH in triangular form arc to the right, with body turning to right]

P10: “to **achieve an output**” [RH moves horizontally to the right]

P3: “**if it fails the condition.**” [RH arcs from right to move slightly to the left and point left]

The left to right transverse as a metaphor was seen as time-based processes in participants’ gestures for loops. In total, 14 out of 16 participants moved one or both hands in a circle when discussing loops (as well as other iterative processes). For 9 participants (P2; P4; P5; P6 P7; P8; P9; P11; P16), this circular gesture was clockwise on a transversal axis (Figures 9a; 9b, 9c.) These clockwise gestures were interpreted as left to right because a) gestures began by moving left to right, b) the left to right arc was often more pronounced, c) the hand would often move to the right whilst rotating clockwise. There was, nevertheless, one exception to the clockwise gesture: P7 created an anticlockwise gesture. This participant was talking about “*loops in a program where the program does kind of screwing up [sic]*”, and moreover, they later created a clockwise gesture when discussing loops.

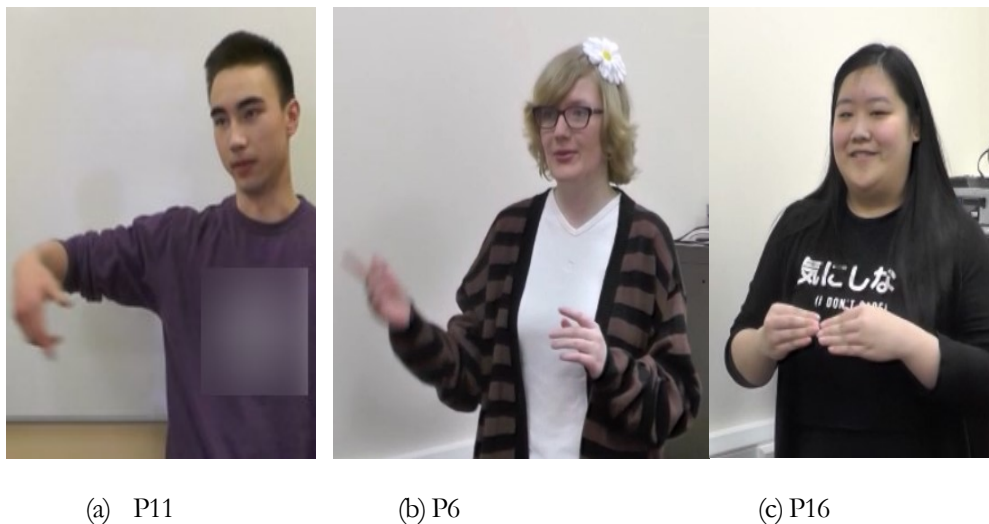


Fig. 9. Clockwise rotating gesture for loops ((a) P11 (b) P16 and (c) P16

P11: “Kinda similar to an **algorithm**” [RH Finger rotates three times clockwise]

P6: “when a **program goes through the same process over and over again**” [RH with extended finger rotates clockwise from body to the side]

P16: “when you are **calling the instruction over and over at the same time**” [BH rotating clockwise in front of body]

Frontal axis: pathway forwards from the body

Although the clockwise gestures for loops described in the previous section were predominately transversal, many did angle slightly outwards. Moreover, for 7 participants (P1; P5; P9; P10; P12; P13; P14), the circular gesture for loops was projected forward away from the body on a frontal axis (Figure 10a), where the forward motion was emphasized.

Similar to the transversal circular gesture, this gesture was used not only to talk about loops but other processes (Figure 10b).

As well as rotating circular gestures, participants often displayed simpler straight or arced gestures in front of themselves when describing computing processes. In the couple of instances when participants created a gesture moving back toward their body, their language corresponded to a process of checking back on a process (Figure 10c). Consequently, this supports the proposition that participants were drawing upon a general body-based spatial metaphor of time (future is in front of us) to conceptualize computing processes.



(a) P10

(b) P6

(c) P9

Fig. 10. Gesturing using frontal axis as a metaphor for time ((a) P10 (b) P6 and (c) P9

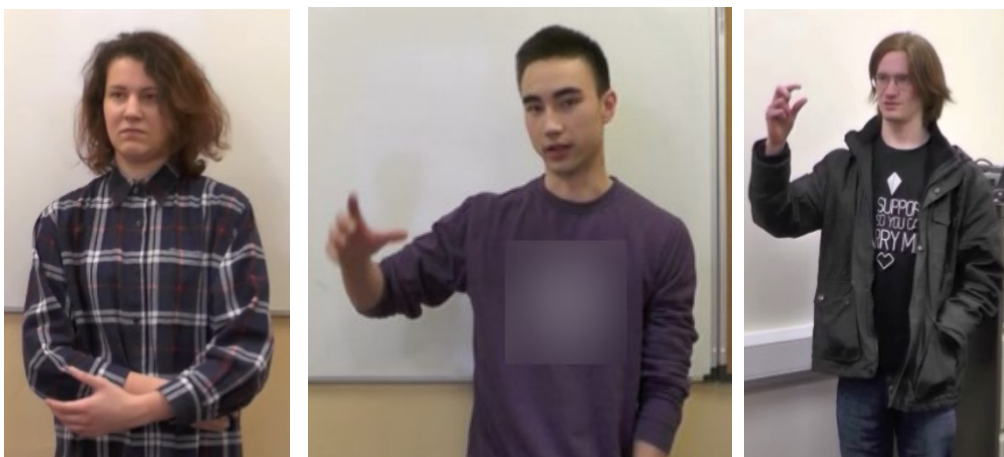
P10: “which has to be **true** if the loop is to be repeated” [RH rotating forward]

P6: “or counting up to something” [BH rotating forward]

P9: “**checks** afterwards” [RH finger points back to body]

3.2.3 Conceptual integration: computing constructs within a process

Our findings show two overarching conceptual metaphors evident in participants’ explanations: *Computing Constructs as Physical Objects*, and *Computing Processes as Motion along a Path*. The participants also demonstrated gestures that were an integration of both these metaphors. In these gestures, participants would simulate grasping or pinching an object then, while maintaining this hand form, trace a trajectory along one of the axes discussed. For example, Participant 11, when explaining what an algorithm was, created a pinch gesture for “steps”, and then circled this hand forward when talking about these repeating (Figure 11a). The same participant later simulated grasping a larger object when referring to an ‘IF statement’, then simulated moving this object to her right side when describing how it functioned. Similarly, Participant 10 created a pinch hand form for loop and rotated his hand (Figure 11b). P15 used both hands to simulate pinching a loop, then moved this in steps to the right of her body. Other examples, including participants P1 (Figures 11c), P11 and P4 described algorithmic steps by pinching an imaginary object and moving the pinched hand down in progressive steps.



(a) P12

(b) P11

(c) P1

Fig. 11. Integrating metaphors in gestures ((a) P12 (b) P11 and (c) P1

P11: “a certain amount of **steps that you keep on repeating**” [LH forms a grasp then rotates forward from the body twice]

P10: “**Loop** are section (sic) of code that execute” [RH creates a pinch then rotates forward from body in a single circle]

P1: “**each step will be distinct**” [RH creates a sequence of four steps one below the other]

4. Discussion

To address the research question: *what types of embodied metaphors, if any, do individuals generate when explaining elementary computing concepts?* we asked 16 computer science students to explain their understanding of three elementary computing concepts, and analysed the spontaneous gestures generated in these explanations. Although the sample was relatively small, the study demonstrated the rich source of data generated by participants in the form of representational gesture. Whilst much work has adopted the methodological approach of this paper in other STEM areas, notably mathematics and science, there has been a notable absence in computer science, possibly attributable to its more recent development as a conceptual domain. Hence, a key contribution of this paper is draw attention to the potential of gesture research to develop our understanding of the conceptual underpinnings of computer science and how this may be supported.

In a total of 48 explanations (16 participants \times 3 concepts), the study identified 368 representational gestures generated in the absence of ‘relevant stimuli’, e.g., a screen/board to point to. Because computing concepts have often been presented as abstract, our findings supports a key claim of Embodied Cognition, that offline thinking involves mental simulations of perception and action (Alibali & Nathan, 2011; Wilson, 2002). Importantly, the representational nature of these gestures provides additional information to speech with which to analyse the nature of thinking in this domain. The findings from our work supports suggestions that the Learning Sciences, and more specifically Embodied Cognition, may offer insight into computing education (e.g., Grover & Pea, 2013; Landy et al., 2014). Computing science education requires greater understanding of conceptual development, and as Niebert et al (2012) claim, “understanding needs embodiment”.

The participants in this study generated an encouraging number of gestures (although not normally distributed across participants). This enabled various patterns of gestures to be identified which warrant further investigation with a larger, more representative sample. Patterns included the use of a circular gesture to communicate re-iteration, spatial groups to represent balancing of clauses, or different hands grasps to refer to different sized constructs. Many of these gesture

patterns can be related to work in other domains, for example, the pinched hand gesture is illustrated as an example of a “factor reference” gesture in Cooperrider et al’s (2016) investigation of individuals’ complex relational reasoning.

We have argued in this paper that the range of representational gestures appear grounded upon two image schemas, the container and path-source-goal schema. Perhaps unsurprisingly, these image schemas are proposed to underpin mathematical concepts (Núñez & Lakoff, 2000), and the metaphors identified from this study are closely relatable to two conceptual metaphors proposed for arithmetic: *Arithmetic as Object Collection* and *Arithmetic as Motion along a Path*. Such metaphorical similarity is, arguably, to be expected. Indeed, two participants explicitly compared computing constructs (e.g., formulae) to mathematics in their explanations. Yet, differences in the metaphors are also revealing. For example, participants’ gestures related to holding single objects of different sizes, rather than simulating manipulation of object collections. When participants did simulate manipulating more than one object, their actions suggest a more complex relationship between constructs; for example, putting one object inside another object (e.g., into a program), holding two objects simultaneously (e.g., IF and THEN), or using both hands to collect ‘input’ toward the body. Future work may further investigate these spatial relationships in computing concepts.

In contrast to gestures manipulating objects, gestures in which participants moved one or both hands along a linear axis typically referred to a computing process (rather than discrete constructs). Revealingly, gestures marked both the start and end points of a process, and a sequence of steps along a process. The axis of the delineated path is also interesting, where a longitudinal axis corresponds with vertical lines of code, a transversal axis corresponds with a cultural left-right direction of time/magnitude seen in other domains from reading to mathematics, and a frontal axis appeared to correspond to a cultural metaphor of time in relation to the body. Although gestures along these axes seemed to simulate processes, it is interesting to note the points made along the trajectory because they often corresponded to algorithmic steps. Further, two participants moved their hands in counter direction (i.e., right-left) when referring to programs having bugs or looping back to previous instructions.

Because the metaphors we identified refer to constructs and processes, we would expect some gestures to integrate these metaphors to communicate a *construct within a process*. For example, four participants gestures illustrated segments of code progressing in steps one after another, or input (as a bounded object) preceding a similarly bounded output. There may well be other examples of integrated metaphors that may communicate computational constructs within a process for example, how data are processed, or when sensors are triggered.

4.1 Implications for Instruction

We investigated the representational gestures used by individuals when explaining concepts but did not extend to evaluating if and how such gestures supported learning. While some have proposed that such work can develop understanding in science domains (Niebert et al., 2012), we agree that caution is needed in leaping to pedagogical guidelines. However, it is worth looking other fields to consider how our findings may inform pedagogical research in computing education.

4.1.1 *Learners' gestures (and actions)*

While attending to learners' gestures in a busy classroom is challenging, research has shown that teachers can assess understanding by attending to gesture (Kelly et al., 2002). Therefore, the research in this paper provides an indication of how it may be possible to train teachers to glean information about learning and understanding from their students' gestures in computing. Teachers may use this additional source of information to guide their practice. For example, mismatches between learners' speech and gesture can often indicate readiness to learn from instruction (Church, 1999).

As well as observing individuals' spontaneous use of gesture, there may be benefits from explicitly encouraging gesturing by making implicit knowledge explicit (Broaders et al., 2007). It would be interesting therefore to examine whether encouraging novice learners to use particular gestures, such as those identified in this paper, supports their understanding and learning. Such support is significant when considering how some curricula, such England's Department of Education's (2013) Computing Curriculum, expect children as young as 5 to learn concepts such as algorithms. It would be worth investigating therefore whether encouraging children to use particular gestures, such as those identified in this paper, could support learning

It is also important to consider other body-based actions beyond hand gestures. Rather than represent ideas just by using the hands, it may be possible for learners, particularly younger learners, to act out various spatial representations, for example, carrying out a sequence of steps using physical steps, and then arcing around to the start again to re-iterate the steps. Indeed, such physical activity in computing education was previously discussed in relation to Computer Science Unplugged (Bell et al., 2012). There is consequently much potential to link our work to 'unplugged' methods for computing education by considering the congruency between certain embodied activities and the target computing concepts (see Skulmowski & Rey, 2018). The contribution of this research therefore may be to encourage greater reflection of the mappings between certain physical actions and the computing concepts being learnt, and the potential

to internalise these actions through gestures. As argued by Roth and Welzel (2001), gesture may be the bridge between action experiences and scientific language.

4.1.2 Teachers' gestures

Gesture research in other domains has demonstrated how teachers themselves frequently gesture, naturally adjust their gestures to scaffold student understanding (Alibali & Nathan, 2007) and that their gestures can improve students' understanding (Valenzano et al., 2003). Our scan of online videos of expert explanations and observations in computing science classes indicates that gestures are indeed common in this domain, although further research may carry out more naturalistic work to evaluate such anecdotal evidence. The implications of the work in this paper are, firstly, to encourage teachers to reflect upon their own gestures, and secondly, to suggest they may be more purposeful in their gestures, possibly being trained to use particular gestures to support understanding, in a similar way to how they may learn to use certain language or visual representations.

4.1.3 Educational materials

Educational software for computing draws upon many visual metaphors to support learners, most notably the use of block-based coding environments as illustrated in Figure 1. An interesting question is whether such environments help generate conceptual metaphors such as *Computing Constructs as Physical Objects*, or are designed to exploit these metaphors. Arguably, there will be an interplay between computing environments and computing metaphors, in which metaphors are used to design environments and then shape the metaphorical thinking of those using them.

The findings from this paper suggests that the design of educational materials in this domain may help learners by exploiting conceptual metaphors. If so, this conceptual lens may be applied to inform further design guidelines, for example, the spatial layout of conditional statements. The lens may also help identify possible conceptual challenges, such as how to visually represent a dynamic representation of a loop.

4.1.4 Embodied Technologies

The capacity for emerging technologies to detect and respond to users' direct, body-based, physical interaction, coupled with increasing research indicating the role of the body in learning, has inspired a new design-based research field exploring the potential of 'embodied learning technologies'. According to Bakker, Antle and Van Den Hoven (2012), a first step in designing a novel embodied learning technology is to identify the underlying embodied metaphors in the target domain. While their work has focused on music, this approach to developing technologies based on prior

empirical work identifying embodied metaphors from gestures has been adopted by others in the field; for example, pioneering work by Abrahamson and colleagues (Abrahamson, 2007; Abrahamson & Trninic, 2011) has built on gesture research to inform the development of gesture recognition technology to support learners' concepts of ratio. While several authors refer to embodiment in their design of innovative computing education applications (e.g., Daily, Leonard, Jörg, Babu, & Gundersen, 2014; Leonard et al., 2015), embodiment seems to be interpreted in terms creating programming sequences through an engaging body-based interface, rather than drawing upon knowledge of how particular computing constructs may be physically represented.

The findings from this paper suggest two overarching 'embodied metaphors': *Computing Constructs as Physical Objects* and *Computing Processes as Motion along a Path*. There are many ways such metaphors could be leveraged through different technologies. Indeed, tangible programming blocks (Bers & Horn, 2009; Sipitakiat & Nusen, 2012) arguably achieve this by using physical objects to represent different constructs (although they may be limited in representing different constructs through different sizes and relationships, e.g., containership). It would also be possible to design gesture-based technologies that enabled children to manipulate computing constructs through grasping/pinching gestures. Such technologies can also be programmed to respond to whole body movements, gesturing a hand forwards to execute the stages of a simple code, or gesturing a loop to create this programming instruction.

4.2 Limitations and future steps

This study was exploratory where it was not certain initially if students would reveal meaning through gesture or whether patterns would emerge. Whilst the prevalence of representational gestures across participants validated the aims of this research study, there are important limitations to note with regard to interpretation of meanings. Some of these limitations can be addressed in future work.

The first limitation to highlight is the lack of other measures of conceptual understanding or procedural ability with which to help interpret the gestures generated by participants. Consequently, there is no means with which to know if, and how, certain gestures relate to ability. Such work is fundamental in evaluating the potential to leverage gestures to assess and support learning. This is particularly the case where concepts comprise of multiple metaphors of increasing complexity, as evident in other scientific concepts such as 'energy' (Close & Scherr, 2015). Further work should therefore adopt a more developmental lens and examine how learners' gestures evolve over time.

As well as examine gestures over time, further work should seek to expand the range and diversity of participants. The sample for this study was relatively small (16) and heterogenous in gender and age and first language (although relatively homogeneous in occupation (computing science students)). Therefore, it is unclear from this study whether explanations and gestures generalise to a wider population, or what factors shaped representational thinking. Certainly, it is important to challenge any assumption that younger learners draw upon, or even benefit from, the same metaphors despite the focus on elementary concepts. As in other domains, it is possible that different metaphors serve to support understanding at different levels.

It is also likely that patterns across participants reflect similar curricula, or the forms of tools and external representations used, which will likely vary substantially across contexts. Similarly, gestures co-occurred with speech, hence it is likely that there is a strong linguistic influence (English). Indeed, much care is needed in generalising findings using the methodological approach of this paper as gesture meanings can differ significantly between cultures (Kendon, 1997). However, whilst understanding these relationships was beyond the remit of this paper, the findings demonstrate the value of such investigation in future work. Indeed, the patterns of gestures across participants in this study does suggest the potential to investigate overlap and differences in shared meanings.

A further limitation of this study that should be considered from a theoretical perspective is the removal of relevant stimuli in interviews to focus on offline thinking. In more naturalistic settings, cognition is likely to be distributed across the environment (e.g., computer visualisations, drawings) or people (e.g., others' gestures). It is therefore important for further work to investigate how embodied meanings shape, and are shaped by, context. How, for example, do visualisations (which are common in computing education) shape gesture production? Does the introduction of various visual metaphors (e.g., block-based coding) shape conceptual thinking? The analysis of learners' gestures during, and after, interaction with different external representations can help address these questions.

It is also important to note that the work reported only focuses on three computing concepts, and whilst these concepts were chosen to be representative of elementary computing concepts, they warrant critical reflection. One key point to note is how two terms: 'loops' and 'conditional statements' have quite familiar meanings independently of computing science, and it is likely that these terms have evolved clearer spatial representations than other computing terms. Yet, data from the concept *algorithm* suggest that individuals will draw upon embodied experiences to conceptualise terms even where spatial relationships are less clear. Further work should examine and compare a more comprehensive range

of concepts, and in doing so identify what factors influence the embodied nature of different computing concepts, and the possible influence of linguistic meaning beyond the domain.

In summary, therefore, future work has much potential to address limitations of the reported study and adopt the methodological lens to examine how gestures vary over time between learners with different cultural and educational experiences. Such work can then provide a foundation to evaluate and inform the design of existing and novel educational interventions. Although exploratory and limited to three concepts, the reported findings can also directly inform future work which may examine how children and their teachers communicate their understanding of core terms such as algorithm, how pedagogical approaches (both materials and teacher communication) develop understanding of these concepts, and the effectiveness of designed interventions – from informing teachers’ gesture to novel learning technologies.

5. Conclusion

Existing research has examined the role and implications of Embodied Cognition for STEM focusing on mathematics and science education. The contribution of this paper is to provide empirical evidence for the embodied nature of computing concepts, and in doing so, draw attention to the potential of this line of investigation for this field. The paper also demonstrates the potential to identify patterns and variation in how individuals express their understanding through gesture. However, caution must be made in generalising the findings in light of participant sampling. Further work may seek to extend this research with larger participant groups, as well as empirically examine the potential to leverage embodied mechanisms in pedagogy and design.

As argued by Grover and Pea (2013), the socio-economic drive to accelerate computing education has created a much-needed gap in theoretical understanding in this domain, a gap they believe can be addressed through Learning Sciences research including in the field of Embodied Cognition. We hope this paper contributes to efforts addressing this gap.

6. Acknowledgements

We would like to thank the participants involved in this study and the Carnegie Trust for the Universities of Scotland (Grant Ref: 70187) for funding the research. We would also like to thank the reviewers of the journal whose reviews greatly contributed to the thinking and writing of this paper.

7. References

- Abrahamson, D. (2007). *From Gesture to Design: Building Cognitively Ergonomic Learning Tools*. Paper presented at the Annual meeting of the International Society for Gesture Studies, Evanston, IL: Northwestern University.
- Abrahamson, D. (2009). Embodied design: Constructing means for constructing meaning. *Educational studies in mathematics*, 70(1), 27-47. doi:10.1007/s 10649-008-9137-1
- Abrahamson, D., & Trninic, D. (2011). *Toward an Embodied-Interaction Design Framework for Mathematical Concepts*. Paper presented at the Proceedings of the 10th International Conference on Interaction Design and Children, Ann Arbor, USA.
- Alibali, M. W., & Nathan, M. J. (2007). Teachers' gestures as a means of scaffolding students' understanding: Evidence from an early algebra lesson. In R. Goldman, R. Pea, B. J. Barron, & S. J. Derry (Eds.), *Video research in the learning sciences*. (pp. 349–365). Mahwah, NJ: Erlbaum.
- Alibali, M. W., & Nathan, M. J. (2011). Embodiment in mathematics teaching and learning: evidence from learners' and teachers' gestures. *Journal of the learning sciences*, 21(2), 247-286. doi:10.1080/10508406.2011.611446
- Amin, T. G. (2015). Conceptual Metaphor and the study of conceptual change: Research synthesis and future directions. *International Journal of Science Education*, 37(5-6), 966-991. doi:10.1080/09500693.2015.1025313
- Amin, T. G., Jeppsson, F., & Haglund, J. (2015). Conceptual Metaphor and Embodied Cognition in science learning: introduction to special issue. *International Journal of Science Education*, 37(5-6), 745-758. doi:10.1080/09500693.2015.1025245
- Bakker, S., Antle, A. N., & Van Den Hoven, E. (2012). Embodied metaphors in tangible interaction design. *Personal and Ubiquitous Computing*, 16(4), 433-449. doi:10.1007/s00779-011-0410-4
- Barsalou, L. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, 22(4), 577-660. doi:10.1017/S0140525X99002149
- Barsalou, L. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617-645. doi:10.1146/annurev.psych.59.103006.093639
- Bell, T. C., Lambert, L., & Marghitu, D. (2012). *CS unplugged, outreach and CS kinesthetic activities*. Paper presented at the Proceedings of the 43rd ACM technical symposium on Computer Science Education (SIGCSE '12), New York, NY, USA.

- Bers, M., & Horn, M. S. (2009). Tangible programming in early childhood: Revisiting developmental assumptions through new technologies. In I. R. Berson & M. J. Berson (Eds.), *High-tech tots: Childhood in a digital world* (pp. 49-70). Greenwich, CT: Information Age Publishing.
- Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology-General*, 136(4), 539-550. doi:10.1037/0096-3445.136.4.539
- Brookes, D. T., & Etkina, E. (2015). The importance of language in students' reasoning about heat in thermodynamic processes. *International Journal of Science Education*, 37(5-6), 759-779. doi:10.1080/09500693.2015.1025246
- Brown, N. C., Sentance, S., Crick, T., & Humphreys, S. (2014). Restart: The resurgence of computer science in UK schools. *ACM Transactions on Computing Education (TOCE)*, 14(2), 9. doi:10.1145/2602484
- Church, R. (1999). Using the relationship between gesture and speech to capture transitions in learning. *Child Development*, 14(2), 313-342. doi:10.1016/S0885-2014(99)00007-6
- Cienki, A. (2005). Image schemas and gesture. *From perception to meaning: Image schemas in cognitive linguistics*, 29, 421-442. doi:10.1515/9783110197532.5.421
- Close, H. G., & Scherr, R. E. (2015). Enacting Conceptual Metaphor through Blending: Learning activities embodying the substance metaphor for energy. *International Journal of Science Education*, 37(5-6), 839-866. doi:10.1080/09500693.2015.1025307
- Cooperider, K., Gentner, D., & Goldin-Meadow, S. (2016). *Gesture reveals spatial analogies during complex relational reasoning*. Paper presented at the 38th Annual Meeting of the Cognitive Science Society, Austin, TX.
- Cortina, T. J. (2015). Reaching a broader population of students through unplugged activities. *Communications of the ACM*, 58(3), 25-27. doi:10.1145/2723671
- Daily, S. B., Leonard, A. E., Jörg, S., Babu, S., & Gundersen, K. (2014). *Dancing alice: Exploring embodied pedagogical strategies for learning computational thinking*. Paper presented at the Proceedings of the 45th ACM technical symposium on Computer science education, Atlanta, GA, USA.
- Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, 122(3), 371-396. doi:10.1037//0096-3445.122.3.371

- Department for Education. (2013). *Computing programmes of study: key stages 1 and 2*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/239033/PRIMARY_national_curriculum_-_Computing.pdf
- Edwards, L. D. (2005). *Metaphors and gestures in fraction talk*. Paper presented at the 4th Congress of the European Society for Research in Mathematics Education, Sant Feliu de Guixols, Spain.
- Edwards, L. D. (2009). Gestures and conceptual integration in mathematical talk. *Educational studies in mathematics*, 70(2), 127-141. doi:10.1007/s10649-008-9124-6
- Eisenberg, M. (2009). *Embodiment as a Strategy for Mathematics Education*. Paper presented at the 8th Interaction Design and Children conference, Como, Italy.
- Flevaris, L. M., & Perry, M. (2001). How many do you see? The use of nonspoken representations in first-grade mathematics lessons. *Journal of Educational Psychology*, 93(2), 330-345. doi:10.1037/0022-0663.93.2.330
- Gentner, D. (1983). Structure-Mapping - a Theoretical Framework for Analogy. *Cognitive Science*, 7(2), 155-170. doi:10.1016/S0364-0213(83)80009-3
- Goldin-Meadow, S. (2009). How gesture promotes learning throughout childhood. *Child Development Perspectives*, 3(2), 106-111. doi:10.1111/j.1750-8606.2009.00088.x
- Goldin-Meadow, S. (2015). From action to abstraction: Gesture as a mechanism of change. *Developmental Review*, 38, 167-184. doi:10.1016/j.dr.2015.07.007
- Goldin-Meadow, S., Cook, S. W., & Mitchell, Z. A. (2009). Gesturing gives children new ideas about math. *Psychological Science*, 20(3), 267. doi:10.1111/j.1467-9280.2009.02297.x
- Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological Science*, 12(6), 516-522. doi:10.1111/1467-9280.00395
- Grover, S., & Pea, R. (2013). Computational Thinking in K-12 A Review of the State of the Field. *Educational Researcher*, 42(1), 38-43. doi:10.3102/0013189X12463051
- Herbert, S., & Pierce, R. (2007). *Video Evidence: What Gestures Tell us About Students' Understanding of Rate of Change*. Paper presented at the Annual Conference of the Mathematics Education Research Group of Australasia, MERGA.

- Hostetter, A. B., Bieda, K., Alibali, M. W., Nathan, M. J., & Knuth, E. J. (2006). *Don't just tell them, show them! Teachers can intentionally alter their instructional gestures*. Paper presented at the Proceedings of the 28th Annual Conference of the Cognitive Science Society.
- Hui, T. H., & Umar, I. N. (2010). *Metaphors and Pair Programming as a Constructivist Strategy in Computing Education: A Literature Review*. Paper presented at the Emerging Trends in Higher Education Learning and Teaching, Kuala Lumpur, Malaysia.
- Hutchins, E. (1995). *Cognition in the Wild*. Cambridge, Massachusetts: MIT press.
- Iverson, J. M., & Goldin-Meadow, S. (1997). What's communication got to do with it? Gesture in children blind from birth. *Developmental Psychology*, 33(3), 453-467. doi:10.1037//0012-1649.33.3.453
- Jeppsson, F., Haglund, J., & Amin, T. G. (2015). Varying use of conceptual metaphors across levels of expertise in thermodynamics. *International Journal of Science Education*, 37(5-6), 780-805. doi:10.1080/09500693.2015.1025247
- Kelly, S. D., Singer, M., Hicks, J., & Goldin-Meadow, S. (2002). A helping hand in assessing children's knowledge: instructing adults to attend to gesture. *Cognition and Instruction*, 20(1), 1-26. doi:10.1207/s1532690xci2001_1
- Kendon, A. (1997). Gesture. *Annual review of anthropology*, 26(1), 109-128. doi:10.1146/annurev.anthro.26.1.109
- Knuth, D. E. (1974). Computer science and its relation to mathematics. *The American Mathematical Monthly*, 81(4), 323-343. doi:10.1300/J025v04n03_17
- Kövecses, Z. (2008). Conceptual metaphor theory Some criticisms and alternative proposals. *Annual review of cognitive linguistics*, 6(1), 168-184. doi:10.1075/arcl.6.08kov
- Kubica, J. (2012). *Computational Fairy Tales*: CreateSpace Independent Publishing Platform.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by* (Vol. 111). University of Chicago Press: Chicago, IL.
- Lakoff, G., & Johnson, M. (1999). *Philosophy in the Flesh* (Vol. 4): New york: Basic books.
- Landy, D., Trninic, D., Soylu, F., Kehoe, J., & Fishwick, P. (2014). *The Implications of Embodiment for Mathematics and Computing Education*. Paper presented at the The 36th annual meeting of the Cognitive Science Society, Quebec City, Canada.
- Leonard, A. E., Dsouza, N., Babu, S. V., Daily, S. B., Jörg, S., Waddell, C., . . . Boggs, K. (2015). Embodying and programming a constellation of multimodal literacy practices: Computational thinking, creative movement, biology, & virtual environment interactions. *Journal of Language and Literacy Education*, 11(2), 64-93.

- Lindgren, R., Manches, A., Abrahamson, D., Price, S., Lee, V., & Tissenbaum, M. (2016). *Embodiment and Designing Learning Environments*. Paper presented at the 12th International Conference of the Learning Sciences, Singapore.
- Lye, S. Y., & Koh, J. H. L. (2014). Review on teaching and learning of computational thinking through programming: What is next for K-12? *Computers in Human Behavior*, 41, 51-61. doi:10.1016/j.chb.2014.09.012
- McNeill, D. (1992). *Hand and mind: what gestures reveal about thought*. Chicago: University of Chicago Press.
- Murphy, C. (2009). The Constructive role of the conceptual metaphor in children's arithmetic: a comparison and contrast of Piagetian and embodied learning perspectives. *Philosophy of Mathematics Education Journal*(22).
- Nemirovsky, R., Rasmussen, C., Sweeney, G., & Wawro, M. (2012). When the classroom floor becomes the complex plane: Addition and multiplication as ways of bodily navigation. *Journal of the learning sciences*, 21(2), 287-323. doi:10.1080/10508406.2011.611445
- Niebert, K., Marsch, S., & Treagust, D. F. (2012). Understanding needs embodiment: A theory-guided reanalysis of the role of metaphors and analogies in understanding science. *Science Education*, 96(5), 849-877. doi:10.1002/sce.21026
- Núñez, R. (2000). *Mathematical Idea Analysis: What Embodied Cognitive Science Can Say about the Human Nature of Mathematics*. Paper presented at the Proceedings of the Conference of the International Group for the Psychology of Mathematics Education (PME), Hiroshima, Japan.
- Núñez, R., & Lakoff, G. (2000). *Where mathematics comes from*. New York: Basic books.
- Núñez, R., & Marghetis, T. (2014). Cognitive Linguistics and the Concept (s) of Number. In R. C. Kadosh & A. Dowker (Eds.), *Oxford Handbook of Numerical Cognition* (pp. 377-401). Oxford: Oxford University Press.
- Núñez, R., & Sweetser, E. (2006). With the future behind them: Convergent evidence from Aymara language and gesture in the crosslinguistic comparison of spatial construals of time. *Cognitive Science*, 30(3), 401-450. doi:10.1207/s15516709cog0000_62.
- Parrill, F., & Sweetser, E. (2004). What we mean by meaning: Conceptual integration in gesture analysis and transcription. *Gesture*, 4(2), 197-219. doi:10.1075/gest.4.2.05par
- Pine, K., Lufkin, N., & Messer, D. (2004). More gestures than answers: Children learning about balance. *Developmental Psychology*, 40(6), 1059-1067. doi:10.1037/0012-1649.40.6.1059

- Pollard, S., & Duvall, R. C. (2006). *Everything I needed to know about teaching I learned in kindergarten: bringing elementary education techniques to undergraduate computer science classes*. Paper presented at the ACM SIGCSE Bulletin.
- Pouw, W. T., van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review*, 26(1), 51-72. doi:10.1007/s10648-014-9255-5
- Román-González, M., Pérez-González, J.-C., & Jiménez-Fernández, C. (2017). Which cognitive abilities underlie computational thinking? Criterion validity of the Computational Thinking Test. *Computers in Human Behavior*, 72, 678-691. doi:10.1016/j.chb.2016.08.047
- Roth, W.-M., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching*, 38(1), 103-136. doi:10.1002/1098-2736(200101)38:1
- Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies*, 45(2), 185-213. doi:10.1006/ijhc.1996.0048
- Sipitakiat, A., & Nusen, N. (2012). *Robo-Blocks: designing debugging abilities in a tangible programming system for early primary school children*. Paper presented at the 11th International Conference on Interaction Design and Children, Bremen, Germany.
- Skulmowski, A., & Rey, G. D. (2018). Embodied learning: introducing a taxonomy based on bodily engagement and task integration. *Cognitive Research: Principles and Implications*, 3(1), 6. doi:10.1186/s41235-018-0092-9
- Stacey, K., Helme, S., & Steinle, V. (2001). *Confusions between decimals, fractions and negative numbers: A consequence of the mirror as a conceptual metaphor in three different ways*. Paper presented at the Proceedings of the 25th Conference of the International Group for the Psychology of Mathematics Education, Utrecht, Netherlands.
- Valenzano, L., Alibali, M. W., & Klatzky, R. (2003). Teachers' gestures facilitate students' learning: A lesson in symmetry. *Contemporary Educational Psychology*, 28(2), 187-204.
- Varela, F. J., Thompson, E., & Rosch, E. (2017). *The embodied mind: Cognitive science and human experience*. MIT press.
- Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), 625-636. doi:10.1080/10508406.2011.553259
- Wing, J. M. (2008). Computational thinking and thinking about computing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366(1881), 3717-3725. doi:10.1098/rsta.2008.0118

Wittenburg, P., Brugman, H., Russel, A., Klassmann, A., & Sloetjes, H. (2006). *Elan: a professional framework for multimodality research*. Paper presented at the 5th International Conference on Language Resources and Evaluation., Paris, France.