A representation approach to conceptualizing tangible learning environments

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ABSTRACT
Tangibles, in the form of physical artefacts embedded with sensor technologies, offer the opportunity to exploit and build on our everyday interaction and experience with the world, enabling new forms of engagement and access to tools for supporting learning. The implications for learning are considerable, potentially bringing about a radical change in the way we conceptualise learning and learning activities. However, we know little about the specific learning benefits, and currently lack an effective structure within which to establish them. Although several frameworks have been proposed for conceptualizing tangible environments, none highlight the central role that external representations have in tangible environments. This paper argues for the importance of placing primary emphasis on representation, and the role that this might play in mediating interaction and cognition in tangible environments. The representation-tangible relationship is outlined, together with their differential potentials for learning. Based on this the paper then proposes a conceptual framework for systematically investigating how different ways of linking digital information with physical artefacts influence interaction and cognition, to gain a clearer understanding of their role for learning.

Author Keywords
Tangible environments, Learning, Representation, Conceptual framework, Cognition.

ACM Classification Keywords
H.5.2 Information interfaces and presentation (e.g., HCI): User Interfaces

INTRODUCTION
With the development of ubiquitous computing, embedding technology in both artefacts and the environment is becoming more commonplace. Tangibles, in the form of physical artefacts embedded with wireless, sensor and actuator technologies, offer the opportunity to build on our everyday interaction and experience with the world. Physical objects coupled with digital information allow access to more or different information than is normally available in the immediate physical environment. Digital information, in the form of sound, narration, images, text or animation, can be flexibly combined with artifacts [47], the environment [37, 44] or action [31, 33] to provide contextually relevant information based on abstract concepts or on enhancing key components of the task or concept with which the user is engaging. The potential for flexibly combining physical artefacts and environments, sensor technologies and representations opens the door to new ways of engaging with learning.

Theories of learning and cognition offer a compelling rationale for the value of tangible and embodied interaction for supporting learning (e.g., see also [27]), being compatible with socio-constructivist theoretical concepts including hands-on engagement; experiential theories of learning [5]; construction of models [28, 35]; collaborative activity and transformative communication [29]. A number of research projects have designed and developed tangible artefacts or environments that focus on different aspects of learning activity, for example, narrative [3], exploration and construction [33, 47], models of phenomena [25], and pattern based interaction [45].

Although the application of tangible computing in various contexts has been clearly demonstrated, there is little research that offers any significant understanding of the differential cognitive costs and benefits of tangible learning environments. Some research has begun to identify ways in which interaction and learning activity might be mediated by representation-device relationships. For example, in the Ambient Wood project representations with more ambiguous mappings promoted higher levels of collaborative reflection through discussion than direct mappings [34], and the value of unexpected or unfamiliar events (between action or artefact and representation) for attracting attention and promoting reflection [32]. However, the real gains from tangible interaction for learning are being questioned [23, 22], and the need for rigorous empirical work, enabling clearer access to and understanding of the effect of tangible computing on learning, is evident. In particular to understand how tangible designs might change the way we perceive and the way we think about concepts being learned. Given the versatility of the space, how can we best achieve this?

A central tenet of tangible environments is the facility to link artefacts with representations. Different forms of representation and representation design are well known to play an important role in cognition. In tangible environments the potential for flexibly combining artefact and representation promises greater representational power. But the flexibility of such coupling brings with it an exponential number of parameters for linking together representation, object or environment, and action. Currently we know little about how the different representation-artefact or environment combinations mediate interaction, action and, of central concern in this paper, cognition. This paper argues that representation-artefact links are the primary concept around which we can gain purchase on the cognitive impact of tangible environments. Taking this as the core concept, a framework for conceptualizing tangible environments is proposed, which focuses on the relationship between different artefact-representation combinations, and the role that they play in shaping cognition.

BACKGROUND

A number of framework and taxonomies for conceptualising tangible user interfaces are emerging [e.g., 41, 17]. Primarily they provide a way of classifying tangible interfaces to describe or compare the different systems, Some are described in terms of underlying properties of physical-digital links in a technical sense [19], or more specifically in identifying cognitive dimensions of tangible user interfaces [10], or as a taxonomy for integrating research [11]. Although the frameworks fundamentally base their classification on physical digital links in some sense, they differ in degree of detail, description and perspective.

Ullmer and Ishii's framework [41] provides a basic model of representational relationships between the digital and the physical and interaction, but doesn't specify the relationships at any level of detail. Three key characteristics of physical and digital relationships are cited:

- Physical representations are coupled with digital information,
- Physical representations embody control of digital representations
- Physical representations are perceptually coupled with mediated digital representations

The coupling relationship between objects and digital information is then defined in terms of "digital bindings", which include the facility for coupling using different forms of digital media and different material properties for physical objects. They also suggest three bases that shape the design of physical representation: pre-existing objects embedded with sensors; purpose built computational objects; and physical artefacts of the domain/ practice of the interface. Ullmer and Ishii's framework provides a high level descriptive taxonomy for configuring different systems, and offers ways of conceptualising the interactive space of tangible interfaces, but does not specify the different ways that this coupling (physical digital links) can take place, and they tend to "leave the nature of this connection as implicit with little reflection on the different ways in which this connection may be manifest" [19]. no focus on representational properties.

Koleva et al. [19] provide a somewhat different perspective of the potential links between digital and physical, specifying the different kinds of links that can take place with a particular focus on how digital and physical objects can be computationally coupled. Their framework is based around the concept of *degree of coherence* between physical and digital objects, and their links and properties i.e., how closely they map onto one another physically and conceptually. Although Koleva et al's framework identifies relationships in tangible systems in more detail, the features are primarily from a systems based perspective and do not take into account the physical design of the physical space nor the representational properties and links in any detail.

Fishkin's [11] framework aims to provide a general taxonomy to address problems of being able to locate, compare and integrate disparate research in the TUI space and by so doing to guide design. Fishkin's approach is from the perspective of defining tangible interfaces in terms of 'levels of tangibility', using a two dimensional taxonomy with metaphor and embodiment as the two axes. Each dimension runs on a continuum, Fishkin claiming that "the higher the levels of these attributes in a system the more tangible it is" (p.348). Embodiment has four levels, which define the relative distance between the physical and digital display. For example, an artefact that is embedded with the digital effect would constitute *full* embodiment, and at the other end of the spectrum an effect occurring in another room or 'over there' is described as *distant*. Metaphor has four levels according to the closeness of how close the effect of user action is to the real world effect of similar actions. However, it could be argued that the metaphor concept makes assumptions about interaction and /or cognition i.e., that direct mapping to the physical world using tools that we are *currently familiar* with is more *powerful*, than what might be termed indirect. Although there may be some confusion between 'familiarity' and the concept of 'direct' interaction, as yet we don't know the impact of other kinds of links on cognition or interaction, to make any claims about their powerfulness. Although the concept of tangibility may be important as a mediating factor in interaction and cognition, it is not sufficient, as it does not take into account the representational properties of the system. Fishkin also relates the level of embodiment to level of cognitive distance, stating that this has to be considered in design depending on the kind of relationship that is wanted. One issue is that we don't yet know the impact of these different 'distances' on either interaction or cognition, nor the impact of multiple combinations, and therefore cannot dependably inform design.

Thus, Ullmer and Ishii [41], Holmquist et al. [16], Koleva et al. [19], and Fishkin [11] all provide descriptive taxonomies, which formulate categories for configuration of different systems, but say little about the relative strengths and weaknesses of different designs in terms of interaction. More recent theoretical approaches have moved beyond taxonomies that focus on defining terms or frameworks that take a structural approach to categorising systems to a stronger focus on human interaction experience, providing an 'interaction' model. Hornecker and Burr [17] provide a framework that serves as an analytical tool that looks at physical space and social interaction with a focus on collaboration. Hornecker and Buur's approach focuses on designing, interaction and exploiting bodily movement. The issue of having to design not only digital representations but also physical tools and their interrelations is highlighted. Edge and Blackwell [10] classify features of tangible environments in terms of their usability for programming languages, identifying design features through their physical properties of expression, but we know little about the impact of such design configurations on knowledge construction in various learning domains.

As yet there is little theoretical work looking specifically at learning with tangibles, and no good framework for empirical research. Indeed, the question of how to explore such environments and need for more principled approaches for supporting research and analysis of tangible environments are widely claimed [e.g., 9, 17]. The key question for learning and cognition is how can we conceptualise tangible interfaces in a way that will enable better insight into the specific value of tangible environments for learning? A central feature of tangible environments is the potential to exploit different forms of representations. External representations are particularly powerful cognitive tools, and their value in conceptualizing the value of tangible environments for learning is central.

THE VALUE OF A REPRESENTATIONAL APPROACH

Little research in tangible environments has placed representation at its centre, the focus of studies frequently being on 'physicality', forms of interaction, motivation and engagement, with few explicating the learning effects. Tangible objects are representational artifacts in themselves, and tangible environments essentially combine some form of external representation with physical objects or environments and related activity. One of the unique features of tangible technologies is the facility to flexibly combine representation with artefacts and the environment increasing the representational capacity and functionality of the environment. An emphasis and focus on representation is central to understanding better the role of tangibles for learning, not only in terms of representation linked to artefacts but also in terms of the manipulative as representation, rather than as an object in itself, and whether switching between the two roles of the manipulative supports the building of a relationship between the manipulative and other representations [43].

Theories of external cognition highlight the important role of external representations in supporting cognition [39], and the key function they can have as mediating tools for supporting problem solving and learning, through forms of computational offloading [20, 4, 8, 46, 1, 30]. External representations (e.g., diagrams) that explicitly depict aspects of a problem, are shown to make problem solving easier, supporting the learner to make inferences, and freeing up cognitive activity to focus on relevant aspects of the task [46]. Much of this research has focused on visual representation, but with the emergence of ubiquitous technologies, interest in the value of other representational media has increased [e.g., 34]. Audio has been found to mediate understanding of large amounts of abstract data in complex systems [6, 13]. Research investigating the use of mobile technology in scientific experimentation has shown how sensor data can be linked to formal representations of scientific phenomena both in the classroom [e.g., 26, 24] and on field trips [15, 14, 38]. Furthermore, tangible environments offer opportunities for capitalizing on physical representations in the form of artifacts [23] conveying newer forms of information when combined with other forms of representation (e.g., visual).

Collectively this suggests a potential increase in the representational power within tangible environments. However, increased representational power intrinsically brings more complex issues with respect to the impact of representation on cognition. Although external representations have been shown to facilitate certain problem solving activity, other research shows a more complex picture with respect to other representations, such as animation [40, 21, 30], a transient media, which demands integration across representations. Features of the artefact-representation relationships in tangible environments make this inherently dynamic in nature, where both physical and digital representations can change in form, space or time. This brings with it other considerations that impact on learning, as the environment is fundamentally multiple representational [e.g., 36, 8, 2] and consists of some level of transient information. This raises issues of increased memory load and subsequent impact on students' inferences [30], multidimensionality [30], integration of multiple representations [e.g., 36, 8], and meaningful linking between physical interaction and abstract conception [7]. Furthermore, explicit depiction of phenomena through external representations (physical and digital) may reduce cognitive computation to such a degree that cognitive effort or active 'working out' is reduced, potentially hindering learning [18].

The approach presented here focuses on representation – mediated through action – representation being a key factor in shaping conceptualization, interpretation, understanding and interaction. The representation-artefact relationships present in tangible environments are briefly outlined below, and then used as a basis for the proposed framework.

ARTEFACT-REPRESENTATION RELATIONSHIPS

Due to the flexible linking of digital and physical information, inherent in ubiquitous environments, the design variability increases, and in particular the different representation-artefact design combinations for supporting interaction (and learning). Here a number of key characteristics of representation-artefact relationships in tangible environments are described.

- Digital augmentation (in the form of representations) related to objects, actions or the environment can be spatially coupled (or located) in different ways: *(i)* within the object itself, e.g., an embedded light sensor causing an object to light up under certain conditions, e.g., flow blocks [47]; *(ii)* a surface on which an object is being manipulated can be used to display digital changes e.g., Illuminating Light [42]; or a digital representation can be displayed on an adjacent screen [e.g., 12]. These are all visual representations, but other media can be used, adding to the spatial coupling parameters, for example, augmentation through haptic or tactile feedback is likely to be embedded in an object, whereas sound can be distributed across a 'whole' environment space. Furthermore, representations can be simultaneously spatially coupled in multiple ways, for example, using both sound and image.
- Information can be coupled between artefact and representation in different ways. Information can be intentionally accessed through conscious action of the learner. For example, deliberately moving two objects together to cause a particular response, or taking environmental measurements with digital probes). Or information can be unintentionally triggered according to designated criteria, e.g., at a particular moment in time, location, or related to action. For example, the Ambient Horn [34] conveyed contextually relevant sounds triggered according to student location in a woodland; Frequency 1550 [44], enabled children to experience medieval Amsterdam through historical information on their mobile phones elicited according to location in the city.
- The opportunity for flexible use of representations in terms of modality, expression, and time. Although, these features exist in traditional digital environments, when combined with physical artefacts and action, may have a distinct impact on interactivity and cognition. In addition, pervasive technologies have provided the opportunity for more distributed use within the environment and innovative use of other media, such as audio and tactile experiences. The potential for tactile forms of representation, as well as visual or audio, particularly in relation to the impact of the physical properties of manipulated objects on learning e.g., the nature of material the object is made from, or augmentation through vibration, resistance, texture.

THE FRAMEWORK

The framework proposed here builds on concepts drawn from the frameworks described above, and seeks to address some of the issues raised, by focusing the unique property of tangible environments - the external representation-artefact relationship, as a way of concpetualising physical-digital links. Based on previous work [30, 34, 31, 32], the framework provides a more detailed specification of the representation-artefact relationships present in tangible systems in order to identify the properties of the environment. It offers a comprehensive focus on different physical-digital couplings that occur not only in terms of physical distance, but also in terms of networking and information flow, and the symbolic nature of the artefacts (cf. Fishkin's [11] concept of embodiment). To make these distinctions, features of digital manipulatives are identified in terms of *location*, *dynamics, correspondence,* and *modality* identifying the different levels of association that can occur in tangible environments.

Location

This parameter refers to the different location couplings between physical artefacts and digital representations. How do these couplings impact on learning, e.g., do learners make different inferences or interact with information in different ways e.g., level of reflection, or exploration?

Discrete

Input and output are located separately, i.e., a manipulated object triggers a digital representation on an adjacent screen. An example of discrete coupling can be seen in Chromarium, a tangible environment to support children's exploration of colour mixing used an adjacent digital display to show the effects of mixing colours on cubes embedded with RFID technology [12].

Co-located

Input and output are contiguous, i.e., the digital effect is directly adjacent to the artefact. For example, Urp, a model urban planning environment displays effects of architectural structures, such as shadows, or wind patterns onto a surrounding horizontal table surface [42].

Embedded

A digital effect occurs within an object, e.g. the object lights up, moves, exerts force or changes shape or colour according to actions placed upon it. For example, Flow Blocks are sensor embedded blocks, that when connected together send light signals through the blocks, to help children explore different causal structures [47].

Dynamics

This parameter refers to the different information associations that can be created between artefact and representation. How do levels of 'association' affect learners' engagement with information, degree of reflection, meaningful interpretation and integration of objects, actions and effects, or help create cognitive constraint?

Intentionality

Digital effects can occur contiguously with intentional action, generating an expected effect, or they can be inadvertently triggered according to pre-determined configurations, causing an unexpected effect (cf. 'hidden augmentation' [10]). Inadvertent elicitation may engender discovery or discussion [34], but how well do learners integrate unexpected effects into their activity and what is the impact on attention and conceptual understanding?

Cumulation

Representation and meaning changing or developing over time through continued interaction with artefacts, and/or cumulative information recorded by the system from a series of events or learner interaction. Such feedback, dependent on multiple actions, often occurs with a time delay. What kind of inferences are elicited here e.g., the conception that real time delays occur for the event that is being symbolised?

Correspondence

Physical correspondence

This parameter refers to the degree to which the physical properties of the objects are closely mapped to the learning concepts. This is similar to structural correspondence (the degree to which the physical structure is closely mapped to the information structure [edge]), but the emphasis here is on the degree of correspondence to the metaphor of the learning domain. How does this constrain or influence inferences and conceptual understanding of the learning domain?

- Symbolic: defines objects that act as common signifiers, e.g., blocks, used to represent various entities, where the object may have little or no characteristics of the entity it represents. For example a block could represent a book or abstract entities, like chromosomes or circuit components.
- Literal: defines objects whose physical properties are closely mapped to the metaphor of the domain it is representing. For example, a rigid block representing chromosomes reveals none of the fragility or separation that is inherent in the process of genetic changes, whereas loosely magnetically connected 'strips' could convey underlying 'fragile' features of the learning concept.

Representational correspondence

This parameter encompasses design considerations of the representations themselves and how this corresponds to the artefact and action within the context or subject domain of use. Meaning mappings between physical and digital representations can be designed such that the representations themselves differ in levels of association (direct to ambiguous) between symbol and symbolised according to the concept being displayed, or indeed the desired interaction/reflection. For example, research suggests that ambiguous mappings between sound and environment engender different levels of reflection about meaning in context than direct mappings [34].

Modality

Although, the visual mode is often a predominant form of representation [2] the potential for audio and tactile modes in tangible computing requires a broader understanding of their role for learning. A key issue here is to understand the value of the different representation modalities in conjunction with artefact interaction, i.e., visual (image, animation, simulation, text), audio (verbal, non-verbal sound), and tactile.

APPLYING THE FRAMEWORK

Although the framework essentially illustrates the different representational possibilities associated with artefacts in tangible systems, the aim of the framework is to provide a structure within which research can be positioned rather than to provide a prescriptive comparative system for research, which demands consistency of metaphor across the tangible interfaces. The different artefact-representation relations in tangible interfaces inherently contain different metaphorical associations. For example, let us imagine portraying friction on a moving object in a tangible environment. Different representation-artefact relations will lend themselves to different kinds of metaphor. Thus, friction on an object, likened to the object moving through a room full of balls, having to push the balls out of the way, could be illustrated on an adjacent visual display (discrete); or as an abstract animation of air resistance on the surface adjacent to the manipulated object (co-located); or a changes in colour on the surface of the object or even physical resistance as it is pushed through the air (embedded). This quality means that maintaining consistency of metaphor across the tangible interfaces is not always possible. In addition, design of specific domains or activities will lend themselves to particular kinds of artefact-representation combinations more than others, for example, an animation or simulation might reasonably be represented as discrete or co-located representations, but not embedded. One of the interesting properties of artefact-representation combinations in tangible environments is precisely that they offer different metaphorical and representational possibilities. Given the constraints and possibilities of such differential designs, the best way to address this is, not to make like for like comparisons in a representational or metaphorical sense but to investigate the impact of the different features of the tangible environment on areas of interaction being considered. For example, if looking at cognition, the focus of analysis may be on the kinds of inferences, understanding and knowledge construction that each form of representation (and corresponding metaphor) engenders.

One example of how the framework might be used can be shown through exploring the use of tangible-representation combinations to support understanding sound or light wave behaviour. In particular, looking at how waves behave in relation to different substances or materials, such as, glass, rock, sponge or cloth. For example, understanding how light waves are transmitted through substances, how they change the beam, and what happens to the beam after it exits the object. To do this a number of different objects made from a variety of substances or materials (literal physical correspondence) could be used, or objects that represent those substances (symbolic physical correspondence); together with a light source; and representations, designed and linked to wave-action-object, to display the effect of the light beam when it comes into contact with the object for each of the *location* framework parameters. Thus, a discrete representation could display an animation, on an adjacent screen, of a light wave corresponding to the physical light source. When an object is placed in its path the animation shows how this changes the direction and/or strength of the light beam. A similar animation could be displayed on a surface adjacent to the activity with the physical objects. One question is whether the different attention demands of each parameter influences their interpretation, and their interaction patterns. For example, it would be reasonable to hypothesise that the co-located display will be easier to attend to while manipulating objects, than having to look at an adjacent display, demanding a shift in focus of attention. However, forcing a shift in focus of attention may engender more exploratory behaviour, as more effort is required to specifically 'work out' what is happening rather than just 'reading off' the display. For the third 'location' parameter the objects or materials themselves can be embedded with representations showing e.g., levels of absorption through lights in the object, changes in colour or emitting sound, when the beams comes into contact. Of interest here is the kinds of inferences that learners can make about the beam beahviour, and whether having the representation embedded in the 'material' facilitates a broader understanding of the characteristics of materials/substances as well as of light beams, or whether the visualization potential of co-located and discrete representations enables clearer interpretation of 'beam' behaviour, or indeed in combining the representation formats facilitates a richer understanding. Of further interest is the kind of interaction that each parameter engenders, in terms of e.g., exploration, reflection or collaboration.

CONCLUSION

This paper acknowledges the clear need for more empirical research to improve our understanding of the specific value of tangible environments for supporting learning, and more generally different forms of interaction. One of the problems in researching complex environments such as these is that they generate research findings that are hard to integrate. Offering a comprehensive framework would help to provide a cohesive set of work for tangible learning and interaction more generally.

This paper recognizes the key role that external representations play in learning, and regards the potential for flexible artefact-representation design combinations to be a unique feature of tangible environments. Representation is, therefore, argued to be central to tangible environments, yet our understanding of their role in mediating learning and interaction is limited. A better understanding of the impact of novel relationships between different designs of tangibles and representations on interaction would help identify the particular learning benefits and disadvantages.

To this end a framework has been devised within which aspects of cognition and interaction can be shown empirically. By focusing on the representation-artefact relationship we get to the core of the interaction and cognition that unfolds in tangible environments. The different features can be identified individually or in combination as they unfold across the learning experience, and serve as a focus for applying analysis. One function of the developed research framework is to enable specification of representation-artefact combinations, precisely to better distinguish the underlying impact of tangible environments on cognition. Such a framework would also be able to support investigation into task, design, domain, and activity and may be generalized to encompass analysis of e.g., forms of interaction, collaboration. This will enable research contributions to offer a more coherent and comprehensive picture of how the underlying mechanisms of tangible environments can support learning. It, thus, provides a medium within which research exploring the effect of interacting tangible environments can take place, and which is useful for both situating empirical studies and as a basis for analysis.

As well as leading to a better understanding of the underlying mechanisms of tangible environments that impact on learning, such research can contribute to informing the design of tangible learning environments, and ways in which they can be integrated into teaching to enhance learning and effective pedagogical practice.

REFERENCES

1. Ainsworth, S., Bibby, P. & Wood, D (2002) Examining the effects of different multiple representational systems in learning primary mathematics. *J. of the Learning Sciences*. 11(1), 25-62.
2. Ainsworth, S. (2006) DeFT: A conceptual framework for learning with multiple representations *Learning and Instruction* 16,(3) 183-198.
3. Annany, M. & Cassell, J. (2001) Telling Tales: A new toy for encouraging written literacy through oral

storytelling. *Presentation at Society for Research in Child Development*, Minneapolis.

4. Bauer, M. & Johnson-Laird, P. (1993) How diagrams can improve reasoning? *Psychological Science* 4, (6), 372-378.
5. Bruner, J. (1973) *Going Beyond the Information Given*. New York: Norton.
6. Childs, E. (2001) The Sonification of Numerical Fluid Flow Simulations. *Proceedings of the 2001 International Conference on Auditory Display*, Finland 2001.
7. Clements, D. (1999) 'Concrete' Manipulatives, Concrete Ideas. *Contemporary Issues in Early Childhood,* 1, 1, 45-60.
8. Cox, R. & Brna, P. (1995) Supporting the Use of External Representations in Problem Solving: the Need for Flexible Learning Environments. *J. of Artificial Intelligence in Education*. 6(2/3).
9. Dourish, P. (2001) *Where The Action Is: The Foundations of Embodied Interaction*. MIT Press.
10. Edge, D. & Blackwell, A. (2006) Correlates of the cognitive dimensions for tangible user interface. *J. of Visual Languages & Computing*, 17(4), 366-394.
11. Fishkin, K. (2004) A taxonomy for and analysis of tangible interfaces. *Personal and Ubiquitous Computing* 8, 347-358
12. Gabrielli, S., Harris, E., Rogers, Y., Scaife, M. & Smith, H. (2001) 'How many ways can you mix colour? Young children's explorations of mixed reality environments'. *CIRCUS* 2001
13. Garcia-Ruiz, M.A. (2001). Using non-speech sounds to convey molecular properties in a virtual environment *International Conference of New Technologies in Science Education* (CINTEC), Aveiro, Portugal, 4-6 July 2001
14. Gay, R., Rieger, R., & Bennington, T. (2002). Using mobile computing to enhance field study. In N. Miyake, R. Hall, and Koschmann, T. (Eds.), *CSCL 2: Carrying forward the conversation* (pp. 507-528). Mahwah. NJ.: Lawrence Erlbaum.
15. Grant, W. (1993) Wireless Coyote: A Computer-Supported Field Trip. *Communications of the ACM*, My 1993, vol.36, No.5.
16. Holmquist, L., Redström, J. & Ljungstrand, P. (1999) Token-Based Access to Digital Information. *First Int. Symp. on Handheld & Ubiquitous Computing*, Karlsruhe, Springer-Verlag, 234-245.
17. Hornecker E, & Buur, J. (2006) Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. *Proc. of CHI 2006*. Montreal. ACM Press, 437-446.
18. Jones (aka Price), S. & Scaife, M (2000) Animated Diagrams: An investigation into the cognitive effects of using animation to illustrate dynamic processes. In M. Anderson & P. Cheng (eds) *Theory & Applications of Diagrams. Lecture Notes in AI,* 1889, Berlin, Springer-Verlag. 231-244.
19. Koleva, B, Benford, S, Hui Ng, K. & Rodden, T. (2003) A Framework for Tangible User Interfaces. *Physical Interaction Workshop on Real World User Interfaces. Mobile HCI,* Udine, Italy
20. Larkin, J. & Simon, H. (1987) Why a diagram is (sometimes) worth ten thousand words *Cognitive Science* 11, 69-100
21. Lowe, R. (1999) Extracting information from an animation during complex visual learning. *European Journal of Psychology of Education* Vol. XIV, 2, 225-244.
22. Marshall, P., Price, S., & Rogers, Y. (2003). Conceptualising tangibles to support learning. *Proceedings of Interaction Design and Children*, Preston, England, July 1-3, pp 101-110
23. Marshall, P. (2007) Do tangible interfaces enhance learning? In *Proc. 1st international conference on Tangible and embedded interaction*. Louisiana, Feb 15-17, 163 - 170.
24. Metcalf, S. J., & Tinker, R. (2003). *TEEMSS: Technology Enhanced Elementary and Middle School Science*. Presentation at the Annual Meeting of the National Association for Research in Science Teaching, Philadelphia: PA.
25. Moher, T., Hussain, S., Halter, T., & Kilb, D. (2005). RoomQuake: Embedding dynamic phenomena within the physical space of an elementary school classroom. *Conf. on Human Factors in Computing Systems*. 1655-1668, ACM Press.
26. Novak, A., Gleason, C., Mahoney, J., & Krajcik, J. (2002) Inquiry Through Portable Technology. *Science Scope* Nov/Dec 2002
27. O'Malley, C. & Stanton-Fraser, D. (2004) Literature Review in Learning with Tangible Technologies. NESTA *Nesta Futurelab,* 12.
28. Papert, S. (1980) *Mindstorms: Children, computers and powerful ideas*. NY, Basic Books.
29. Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *Journal of the Learning Sciences*, 3(3), 285-299
30. Price, S. (2002) Animated Diagrams: How effective are explicit dynamics for learners? In P. Bell, R. Stevens, & T. Satwitz (eds), *Keeping Learning Complex: The Proceedings of the Fifth International Conference of the Learning Sciences* (ICLS) 344-351. Mahwah, NJ: Erlbaum.

31. Price, S. & Rogers, Y. (2003) Let's get physical: the learning benefits of interacting in digitally augmented physical spaces. In (eds) J. Underwood & J. Gardner, *Computers & Education: Special issue:21st Century Learning*: 43, 137-151

32. Price, S., Rogers, Y., Scaife, M., Stanton, D. & Neale, H. (2003) Using 'tangibles' to promote novel forms of playful learning. *Interacting with Computers*, 15/2, May 2003, 169-185.

33. Raffle, H., Parkes, A., Ishii, H. & Lifton, J. (2006) Beyond record and play. Backpacks: Tangible Modulators for Kinetic Behavior. *CHI 2006 April,* Montreal, Canada.

34. Randell, C. Price, S. Rogers, Y. Harris. E. & Fitzpatrick, G (2004) The Ambient Horn: Designing a novel audio-based learning experience, *Personal and Ubiquitous Computing*. 8, 3, 144-161.

35. Resnick, M. Martin, F. Sargent, R. & Silverman, B. (1996) Programmable Bricks: Toys to Think With. *IBM Systems Journal* 35, 3-4.

36. Rogers, Y. & Scaife, M.(1998) How can interactive multimedia facilitate learning? In Lee, J.(ed.) *Intelligence & Multimodality in Multimedia Interfaces: Research & Applications*. AAAI.

37. Rogers, Y., Scaife, M., Harris, E., Phelps, T., Price, S., Smith, H., et al. (2002). Things aren't what they seem to be: Innovation through technology inspiration. *Proceedings of DIS'2002 Designing Interactive Systems* (pp. 373-379). New York: ACM Press.

38. Rogers, Y., Price, S., Randell, C., Stanton-Fraser, D., Weal, M., & Fitzpatrick, G. (2005) Ubi-learning Integrates Indoor and Outdoor Experiences, *Communications of the ACM*. January 2005, Vol 48, No. 1, 55-59

39. Scaife, M & Rogers, Y (1996) External Cognition: how do graphical representations work? Int. J. of Human-Computer Studies 45, 185-213.Stephan, J. (1996) Targeting Students' Science Misconceptions: Physical Science Concepts Using the Conceptual Change Model. Riverview.

40. Stenning, K. (1998) Distinguishing Semantic from Processing Explanations of Usability of Representations: Applying Expressiveness Analysis to Animation. In (eds.) J. Lee, Intelligence and Multimodality in Multimedia Interfaces: Research and Applications, AAAI Press.

41. Ullmer, B. & Ishii, H. (2001) Emerging frameworks for tangible user interfaces. Carroll, J. ed. *Human Computer Interaction in the New Millenium*, Allison-Wesley, 2001, 579-601.

42. Underkoffler, J. & Ishii, H. (1999) Urp: A Luminous-Tangible Workbench for Urban Planning and Design *Proceedings of CHI*, May 15-19

43. Uttal, W. R. (2003). Psychomythics: Sources of artifacts and misconceptions in scientific psychology. Mahwah, NJ: Lawrence Erlbaum, Inc.

44. WAAG Society, (2005) retrieved October 2nd 2007 http://freq1550.waag.org/

45. Yonemoto, S., Yotsumoto, T. & Taniguchi, R. (2006) A Tangible Interface for Hands-on Learning, *Tenth Int. Conf. on Information Visualisation* iv, 535-538.

46. Zhang, J. & Norman, D. (1994) Representations in distributed cognitive tasks. *Cognitive Science* 18, 87-122.

47. Zuckerman, O. Grotzer, T. & Leahy, K. (2006) Flow blocks as a conceptual bridge between understanding the structure and behavior of a complex causal system. *Proc. of the 7th Int. Conf. Learning Sciences* Indiana, 880-886.