Design and Physicality – Towards an Understanding of Physicality in Design and Use

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Background

We live in an increasingly digital world, yet our bodies and minds are naturally designed to interact with the physical. When designing purely physical artefacts we do not necessarily have to understand what it is about their physicality that makes them work – they simply have it. However, as we design hybrid physical/digital products we now have to understand what we lose or confuse by the added digitality; and so need to understand physicality more clearly than before. The Design for Physicality (DEPtH) project set out to develop new insights into our relationship with the physical.

The roots of DEPtH lie in the coincidentally convergent interests of two research streams: those of the human computer interaction (HCI) researchers at Lancaster under DEPtH's Principal Investigator Alan Dix and product design researchers at University of Wales Institute, Cardiff (UWIC) under Steve Gill (one of the Co-Investigators). The rest of the team were: Hans Gellersen (Co-Investigator), Devina Ramduny-Ellis (Research Associate) and Jo Hare (Research Assistant). Together they were able to muster a wide range of knowledge and experience including product design practice, mathematical modelling, human interface design, ubiquitous computing, lab-based user experiments and social-science methodology.

How we all became involved

Work at Lancaster, prior to DEPtH, included studies of devices: uncovering the tacit knowledge in the selection and use of knobs, dials, switches etc;[1,2] artefacts: analysing role of paper and other physical

[1] GHAZALI, M. and DIX, A., 2005. Knowledge of Today for the Design of Tomorrow. *In: The Bigger Picture: Proceedings of the 2nd International Design and Engagability Conference (IDEC2), 19th British HCI Group Annual Conference, Edinburgh, 5–9 September 2005*. London: Springer Verlag.

[2] GHAZALI, M. and DIX, A., 2005. Visceral Interaction. *In: The Bigger Picture: Proceedings of the 2nd International Design and Engagability Conference (IDEC2), 19th British HCI Group Annual Conference, Edinburgh, 5–9 September 2005*. London: Springer Verlag, pp. 68–72.

[3] RAMDUNY-ELLIS, D., et al., 2005. Artefacts as designed, artefacts as used: resources for uncovering activity dynamics. *Cognition, Technology and Work, Special Issue on Collaboration in Context: Cognitive and Organizational Artefacts*, 7(2), pp. 76–87.

artefacts in office environments;[3] spatial arrangement: enabling users to reconfigure the layout of physical controls through 'Pin and Play' (now 'VoodooIO'),[4] and work analysis: assessing the role of the physical and digital environment on human work activities.[5,6] All these strands, in different ways, emphasised the importance of physical objects located in physical space, and their confluence was the springboard for the first international workshop on Physicality in February 2006[7] that itself was the conception point for DEPtH.

At UWIC, Steve's research group Programme for Interactive Prototype Research (PAIPR) had been working on rapid physical prototype based design and development techniques for information appliances, and understanding the problems faced by designers.[8] Early physical prototypes are often lacking due to a shortage of necessary skills and the disparate nature of the knowledge required,[9] thus flaws are not noticed until so far in the process. To address this shortfall, the *IE System was developed,* which reduced prototyping time from days to hours.[10] The group then moved on to examine the notion of isolating and defining physicality's importance; how it might be investigated, even, possibly measured.

Both Lancaster and UWIC became aware of each other's interest in physicality when Steve was invited to deliver one of the keynote addresses at the Physicality 2006 workshop.

Our motivations

Our motivation for this project was largely practical: how can an effective understanding of physicality and its use and role in design help designers do their job better, and help users have more fulfilling experience with devices? The design process angle flowed more from UWIC's work on prototyping, whilst the use of devices came from Lancaster's work. However, both were clearly interdependent. In fact, within DEPtH, some activities were focused more on one perspective, and some on the other, but in terms of analysis and conceptual understanding, our minds were open to both perspectives and the way they interrelate.

In addition, we had a theoretical perspective: how do humans understand the physical world? How does this understanding translate itself into using digital and hybrid products? What are the critical aspects of physicality that are essential to meaningful interaction? These are questions which flow into the practical side of the project, but are also fascinating in themselves, touching issues of cognitive psychology, social science and philosophy.

[4] VILLAR, N. and GELLERSON, H., 2007. A Malleable Control Structure for Softwired User Interfaces. *In: Proceedings of the First International Conference on Tangible and Embedded Interaction, TEI '07, Baton Rouge, 15–17 February 2007*. New York: ACM Press.

[5] DIX, A., RAMDUNY, D. and WILKINSON, J., 1998. Interaction in the large. *Interacting with Computers – Special Issue on Temporal Aspects of Usability,* 11(1), pp. 9–32.

[6] DIX, A., RAMDUNY-ELLIS, D. and WILKINSON, J., 2004. Trigger Analysis – Understanding Broken Tasks. *In:* D. DIAPER and N. STANTON (eds.), *The Handbook of Task Analysis for Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 381–400.

[7] GHAZALI, M., et al., 2006. *In:* M. BUSCHER (ed.), *Physicality 2006: Proceedings of the First International Workshop on Physicality, Lancaster, 7 February 2006*. Lancaster: Computer Department, Lancaster University.

[8] GILL, S., LOUDON, G. and WALKER, D., 2008. Designing a design tool – working with industry to create an information appliance design methodology. *Journal of Design Research*, 7(2), pp. 97–119.

[9] GILL, S., 2003. Developing information appliance design tools for designers. *Personal and Ubiquitous Computing,* 7(3–4), pp. 159–162.

[10] GILL, S., et al., 2005. How to Design and Prototype an Information Appliance in 24 Hours – Integrating Product and Interface Design Processes. I*n: Proceedings of the 6th International Conference on Computer-Aided Industrial Design and Conceptual Design, Delft, 29 May–1 June 2005*.

Special considerations associated with assembling an interdisciplinary project team.

Both Lancaster and UWIC were engaged in work that bridged rigid disciplinary barriers; however, engaging with one another's viewpoints has not been so difficult. We were brought together partly by good fortune and partly through the Physicality 2006 workshop. In fact, the significance of this workshop in the formation of the team prefigures the critical importance within DEPtH of community engagement through events. Indeed, as we shall discuss later, events have been a source of expert knowledge and empirical data, but also a means of 'giving back' to the community, enabling the sorts of serendipitous contacts that brought us together.

Context

Surely by now we know sufficient about the physical for ordinary product design? While this may be true of the physical properties themselves, it is not the fact for the way people interact with, and rely on, those properties. It is only when the nature of physicality is perturbed by the unusual (and in particular the digital) that it becomes clear what is, and is not, central to our understanding of the world.

Increasingly, digital aspects of physical products mean that causal effects are created programmatically rather than mechanically. Users are thus faced with objects that are partly physical (hold it, touch it, push it) and partly digital (things happen). Even hidden physical mechanisms can be confusing, more so when the linkage between cause and effect is electronic. Arguably it is not necessary to have a theoretical understanding of physicality in order to design; designers may (and do) embody tacit understanding of users' perceptions of physicality in their digital products. However, it is clear that even in relatively simple products this tacit understanding is not complete; for example, when toast burns, the instinctive reaction is to attempt to lift the handle you used to press the toast down, rather than the separate 'stop' button that would pop up the toast. (The toaster is violating the 'natural inverse' property of physical things, i.e. that opposite actions usually have opposite effects).

DEPtH's aim was thus to create a broad model and framework to understand the space of issues and knowledge. However, we sought coherence and coverage, not completeness.

[11] WEISER, M., 1991. The Computer for the Twenty-First Century. *Scientific American,* September 1991.

[12] CHALMERS, D., et al., 2006. *Ubiquitous Computing: Experience, Design and Science* [online]. Available at: <http://www-dse.doc.ic.ac.uk/Projects/UbiNet/GC/index.html>. [Accessed 23 February 2006].

[13] ISHII, H. and ULLMER, B., 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. *In:* S. PEMBERTON (ed.), *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Atlanta, 22–27 May 1997*. New York: ACM Press.

[14] WARWICK, K., 2003. A study in cyborgs. *Ingenia,* 16, pp. 15–22.

[15] STELARC, 1994–2009. Available at: <http://www.stelarc.va.com.au>. [Accessed March 2009].

[16] BENFORD, S., et al., 2005 Expected, sensed, and desired: A framework for designing sensing-based interaction. *Transactions on Computer-Human Interaction*, 12(1), pp. 3–30.

[17] CHALMERS, M. and GALANI, A., 2004. Seamful Interweaving: Heterogeneity in the Theory and Design of Interactive Systems. *In: Proceedings of Designing Interactive Systems, Cambridge, USA, 1–4 August 2004*. New York: ACM Press, pp. 243–252.

Previous work in the area

Despite the sharp increase in research within the ubiquitous computing space,[11] physicality for the user has been largely ignored until recently.[12] Although tangible computing research is closely related, it tends to focus on making computation itself both visible and touchable.[13] Others have explored more intimate connection of the digital with our physical bodies.[14,15]

There are, however, some related conceptual frameworks that have recently emerged.[16,17,18,19,20] Within the design community, the most developed work at DEPtH's inception was Interaction Frogger,[21] which examined the various levels artefacts communicate their potential for action, and more importantly, addressed aesthetic and affective aspects of physical design, rather than just the functional.

Human centred development of computer embedded products or 'information appliances' are at the crossroads of a number of disciplines.[22] The physical and digital interactions are often designed in isolation and only combined for user testing near the end of the development process when major design changes are impossible[23] – hence the need for new tools to overcome the problem.[24] A suite of systems for the development of computer-embedded products have been devised[4,25,26,27,28,29,30] but these have tended to focus more on the electronics or programming base. Prototyping methods[31] go some way towards answering this issue, particularly in their inclusion of physicality; however, methods that retain their 'quick and dirty' hands-on approach while incorporating more accurate simulation are still required.

Looking further back, DEPtH is related to and drew on the ecological psychology perspective. The notion of affordances both in the Gibson sense[32,33] and in the more perceptual sense[34,35] has been very influential in user interface development. Whereas they centre on perceptual–cognitive relationships, the perceptual-motor strand of HCI research focuses on measurements of motor task, drawing on Fitts' law.[36,37]

Gibson's work emphasises perception as an integral part of creatures being actors in the world. In addition, our cognition is itself expressed within the world. Those studying 'distributed cognition' see our cognition and thinking as not just being in our head, but distributed

[18] KOLEVA, B., et al., 2003. A Framework for Tangible User Interfaces. *In:* L. CHITTARO (ed.), *Physical Interaction (PI03) – Workshop on Real World User Interfaces, Proceedings of the Fifth International Symposium on Human Computer Interaction with Mobile Devices and Services, HCI 03, Udine, 8–11 September 2003*. London: Springer Verlag.

[19] ULLMER, B. and ISHII, H., 2000. Emerging frameworks for tangible user interfaces. *IBM System Journal,* 39(3–4), pp. 915–931.

[20] HORNECKER, E., 2005. A Design Theme for Tangible Interaction: Embodied Facilitation. *In:* H. GELLERSEN, et al. (eds.), *Proceedings of the 9th European Conference on Computer-Supported Cooperative Work, Paris, 18–22 September 2005*. London: Springer Verlag.

[21] WENSVEEN, S. A. G., DJAJADININGRAT, J. P. and OVERBEEKE, C. J., 2004. Interaction Frogger: A Design Framework to Couple Action and Function through Feedback and Feedforward. *In: Proceedings of the Designing for Interactive Systems Conference, Cambridge, USA, 1–4 August 2004*. New York: ACM Press, pp. 177–184.

[22] NORMAN, D. A., 1998. *The Invisible Computer: Why Good Products Can Fail, the Personal Computer is so Complex and Information Appliances are the Solution*. Cambridge: MIT Press.

[23] BAXTER, M., 2002. *Product Design: A Practical Guide to Systematic Methods of New Product Development*. Cheltenham: Nelson Thornes.

between our heads, the world and often other people.[38,39] More radically still, some philosophers talk about our mind being embodied; not just physically embodied in our brain, but also in our bodies and the things we manipulate in order to do 'mind-like' things.[40]

Of course work has developed during the lifetime of the project, not least that reported in the proceedings of the Physicality workshops organised by the DEPtH team.

Key research questions

The key objective of DEPtH was to understand those properties of the physical world that are critical to people's ability to manipulate and comprehend ordinary things in their day-to-day life. By understanding these key properties of physicality, the project aimed to inform design process and product. There were two sides to the research: how physicality affects the design process, and how it affects the final designed product.

- *design process* – looking at the level of *fidelity* required of a prototype to accurately mimic a completed information appliance very *quickly,* and the effect of different kinds of materials and digital tools during design. This affects, firstly, the designers themselves – how they work with materials, how they think about their designs; secondly, test users – how effective user testing is with various levels of prototypes; and thirdly, clients to whom putative designs are presented.

- *designed product* – looking at the way end-users can make sense (or not) of the products when digital elements of the design may break what would be 'normal' physical properties, and how to design products so they make best use of a human's ability to interact with the physical word.

During the project we have addressed issues across these areas, with the exception of the impact on clients; it was difficult enough to get designers to talk about their projects let alone to talk to their clients!

Undergirding all of the above is a need to create fundamental conceptual knowledge of the nature of human understanding and engagement with the physical world.

[24] BRANHAM, R., 2000. Given the Radically Changing Work Environment and New Worldviews, What Kinds of New 'Tools' do Designers Need to Survive and Successfully Deal with Tomorrow's Design Problems? *In: Proceedings of IDSA 2000 National Education Conference, Lafayette, USA, 18–20 September 2000*.

[25] GREENBERG, S. and FITCHETT, C., 2001. Phidgets: Easy Development of Physical Interfaces through Physical Widgets. *In:* J. MARKS and E. D. MYNATT (eds.), *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology, Orlando, 11–14 November 2001*. New York: ACM Press, pp. 209–218.

[26] PHIDGETS INC., 2008. Available at: <http://www.phidgets.com>.

[27] PIERCE, J., STEARNS, B. and PAUSCH, R., 1999. Voodoo Dolls: Seamless Interaction at Multiple Scales in Virtual Environments. *In: Proceedings of the 1999 ACM Symposium on Interactive 3D Graphics, Atlanta, 26–28 April 1999*. New York: ACM Press, pp. 141–145.

[28] HARTMANN, B., et al., 2007. Authoring Sensor-based Interactions by Demonstration with Direct Manipulation and Pattern Recognition. *In: Proceedings of ACM CHI 2007 Conference on Human Factors in Computing Systems, San Jose, 28 April–3 May 2007*. New York: ACM Press, pp. 145–154.

[29] AVRAHAMI, D. and HUDSON, S., 2002. Forming Interactivity: A Tool for Rapid Prototyping of Physical Interactive Products. *In: Proceedings of the 4th Conference on Designing Interactive Systems: Processes, Practices, Methods and Techniques, London, 25–28 June 2002*. New York: ACM Press, pp. 141–146.

Methods / Approach / Journey

A medley of methods

The project has used a large number of methods from qualitative observations to formal analysis, reflecting the breadth of the topic and complexity of the issues.

Data gathering/consolidation

Throughout the project, we have been constructing a collection of bibliographic and other resources related to physicality, drawn from literature, workshops organised before and during the project, and our own outputs. This forms the foundation both for a long-term web repository for the community and also for the writing of TouchIT, a 'coffee table' book.

The project has been particularly successful in terms of published outputs, including authoring several journal[8,41,42] and conference papers,[43,44,45,46] editing the Physicality workshop proceedings[47,48,49] and a special issue of the *Interacting with Computers* journal,[50] and the TouchIT book currently being written. However, treating these as purely 'outputs' belies their true significance as part of the project.

Often overlooked, but critical to academic practice, is that the *process* of collating and writing is itself a significant part of the research process. This is particularly true in an interdisciplinary project, where the concrete artefact of the paper or book becomes a locus for interactions, effectively a *boundary* object.[51] Furthermore, the more high level and theoretical concepts often arose out of the process of writing; ideas were not preformed and then communicated, but formed in communication.[52]

Reflective investigations

At various times members of the project team have engaged in reflective investigations – some design activity to explore potential research routes and to shed light on complex design processes. This typically involves the collection of objective outputs and records, but also externalising subjective experience of the process.

The first, the *torch project*, performed early in the project, experimented with new 3D modelling tools: a handheld 3D scanner and the Phantom haptic arm. These tools enabled potters clay to be used to quickly explore and manipulate ideas in relation to the body. The most promising concepts

[30] LANDAY, J. A. and MYERS, B. A., 1995. Interactive Sketching for the Early Stages of User Interface Design. *In: Proceedings of the Conference on Human Factors in Computing Systems, CHI '95, Denver, 7–11 May 1995*. New York: ACM Press.

[31] BUCHENAU, M. and SURI, J. F., 2000. Experience Prototyping. I*n: Proceedings of the 4th Designing Interactive Systems: Processes, Practices, Methods, and Techniques, London, 25–28 June 2002*. New York: ACM Press, pp. 424–433.

[32] GIBSON, J. J., 1979. The Theory of Affordances. *In:* R. SHAW and J. BRANSFORD (eds.), *Perceving, Acting and Knowing: Towards an Ecological Psychology*. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 67–82.

[33] GIBSON, J. J., 1979. *The Ecological Approach to Visual Perception*. Hillside, NJ: Lawrence Erlbaum Associates.

[34] NORMAN, D. A., 1988. *The Psychology of Everyday Things*. New York: Basic Books.

[35] GAVER, W. W., 1991. Technology Affordances. *In:* S. P. ROBERTSON, G. M. OLSON and J. S. OLSON (eds.), *Proceedings of the Conference on Human Factors in Computing Systems: Reaching Through Technology, New Orleans, 27 April–2 May 1991*. New York: ACM Press, pp. 79–84.

[36] FITTS, P., 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology,* 47(6), pp. 381–391.

could be scanned and then edited using a haptic-controlled computer-aided design (CAD) system, Freeform. The final model was printed with a fused deposition modelling (FDM) machine to produce a physical model. A traditional CAD-based model was also constructed. The experience was recorded using a blog.

One clear outcome was the radical way in which the design materials influenced the final design. The standard CAD prototype had a 'functional' feel and was highly symmetrical. In contrast, the prototype from scanned clay was more 'organic', an asymmetric pebble shape that fitted into the hand [Figure 1].

Figure 1, Using advanced tools (i) form by hand (ii) using conventional tools (iii) digitally scan (iv) use Phantom arm haptics to edit digitised solid

The tools are not yet ready for practicing designers, the 3D scanner lacking precisions, and the haptic arm feeling unnatural. However, we speculated whether some sort of physical clay could be created that could transmit its form to modelling software. Developing this was outside the scope of DEPtH, however; since then initial attempts at this sort of clay have been demonstrated at the Tangible and Embedded Interaction Conference (TEI).[53]

The study was influential as the basis of group design exercises at the Physicality 2007 workshop.

[37] CHUA, R., WEEKS, D. J. and GOODMAN, D., 2003. Perceptual-motor Interaction: Some Implications for Human-computer Interaction. *In:* J. A. JACKO and A. SEARS (eds.), *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications (Human Factors and Ergonomics)*. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 23–34.

[38] HOLLAN, J., HUTCHINS, E. AND KIRSH, D, 2000. Distributed cognition: toward a new foundation for human-computer interaction research. *Transactions on Computer-Human Interaction*, 7(2), pp. 174–196.

[39] HUTCHINS, E., 1995. *Cognition in the Wild*. Cambridge, MA: MIT Press.

[40] CLARK, A., 1998. *Being There: Putting Brain, Body and the World Together Again*. Cambridge, MA: MIT Press Cambridge.

[41] DIX, A., et al., 2009. Physigrams: Modelling Devices for Natural Interaction. *Formal Aspects of Computing,* (in press).

[42] RAMDUNY-ELLIS, D., et al., 2009. Physicality in design: an exploration. *The Design Journal,* (in press).

[43] DIX, A., GHAZALI, M. and RAMDUNY-ELLIS, D., 2007. Modelling Devices for Natural Interaction. *In:* P. CURZON and A.CERONE (eds.), *Electronic Notes in Theoretical Computer Science: Proceedings of FMIS 2007 2nd International Workshop on Formal Methods for Interactive Systems, Vol 208C, Lancaster, 4 September 2007*. Oxford: Elsevier, pp. 23–40.

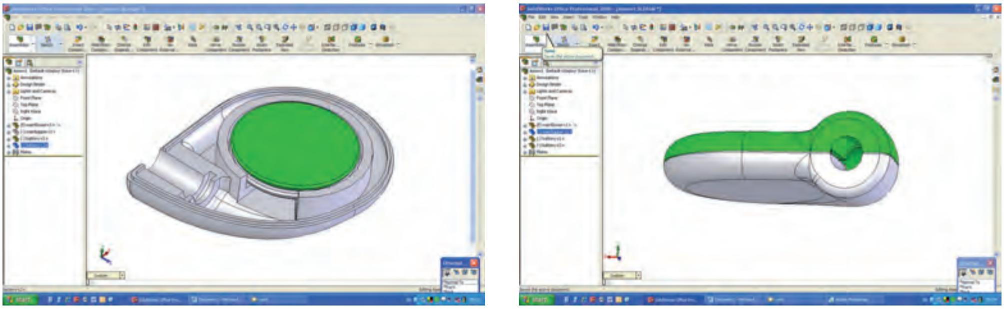


Figure 2, Prototype produced using CAD system

A second reflective investigation (*rotary prototypes*) near the mid-point of the project explored different forms of rotary dials (physical and touch based). We did not take these models further but the ideas were later incorporated in the *Flickr Friend* prototypes and formed the basis of *physigrams in design*, the third reflective investigation (see below).

Ethnographies of practicing designers

We had originally planned to study practicing designers using observational ethnography. However, problems obtaining suitable access prevented all but one (very useful) interview. Access is always a problem in ethnographies as the idea of being observed can be disturbing especially when there may be intellectual property issues involved. However, there may be particular problems studying design itself; because designers often work for third-party clients, they also need to worry about how these clients might construe research observations.

Our intention had been to study what was actually done in design, rather than what designers say they do. We instead addressed this during workshops by taking practicing designers out of the problematic situation of their real workplace.

Workshop programme – engaging with the community

A workshop programme has been at the heart of the DEPtH project, and include an ongoing series of international Physicality workshops[54] and a one-off Physical Fidelity in Design[55] prototyping workshop. The former are essentially academic events, the latter primarily practitioner-led, but both attracted mixed participation. These formed part of the

[44] DIX, A., et al., 2008. Sociality, Physicality and Spatiality: Touching Private and Public Displays. *In: Proceedings of Workshop on Designing Multi-touch Interaction Techniques for Coupled Public and Private Displays, the International Working Conference on Advanced Visual Interfaces, Naples, Italy, 28–30 May 2008*. New York: ACM Press.

[45] RAMDUNY-ELLIS, D., et al., 2008. Exploring Physicality in the Design Process. *In:* D. DURLING, et al. (eds.), *Undisciplined! Proceedings of the Design Research Society Conference 2008, Sheffield, 16–19 July 2008*. Sheffield: Sheffield Hallam University.

[46] HARE, J., et al., 2009. Physical Fidelity: Exploring the Importance of Physicality on Physical-Digital Conceptual Prototyping. *In: Proceedings of the 12th IFIP Conference on Human-Computer Interaction, INTERACT 2009, Uppsala, 24–28 August 2009 (in press)*.

[47] RAMDUNY-ELLIS, D., et al., (eds.), 2007. *Proceedings of Physicality 2007, the Second International Workshop on Physicality, Lancaster, 2–3 September 2007*. Cardiff: UWIC Press.

project's dissemination programme, and nurtured an international community; they are also an integral part of the overall research methodology. DEPtH addresses deeply interdisciplinary issues, hence, it was essential to draw feedback and input from a group beyond the project team.

The Physicality workshops have fed into the DEPtH online repository, and invited speakers brought in perspectives underrepresented in the existing community; for example, the philosopher Mike Wheeler talking on the embodied mind. In addition, the workshops gave us an opportunity to set short design projects.

The two-day Fidelity prototyping workshop was held in our second year and attracted a range of practitioners from design consultancies and blue chip manufacturing companies such as Hewlett Packard and Sony-Ericsson as well as interested academics.

The workshops had tutorial sessions and invited practitioner presentations, but was mainly used to run a 'hack fest' type activity creating physical group prototypes in response to a brief [Figure 3].

Workshops as a resource for data gathering

As noted, the Physicality and Fidelity workshops included group design sessions with experienced practitioners and knowledgeable academics. In both, the processes were closely observed, photographed and videoed. The initial ethnographic observations and field notes carried out on

[48] RAMDUNY-ELLIS, D., et al., 2007. Second International Workshop on Physicality. *In: People and Computers XXI, Volume 2, Proceedings of the 21st British HCI Group Annual Conference, HCI 2007, 3–7 September 2007, Lancaster.* Cardiff: UWIC Press, pp. 217–218.

[49] RAMDUNY-ELLIS, D., et al., 2009. Physicality 2009 – Towards a less-GUI Interface, Third International Workshop on Physicality. *In: Proceedings of the 23rd British HCI Group Annual Conference, HCI 2009, Cambridge, 1–5 September 2009.* (in press).

[50] RAMDUNY-ELLIS, D., et al., (eds.), 2009. *Interacting with Computers, Special Issue on Physicality and Interaction,* 21(1–2), pp. 64–124.

[51] STAR, S. L., 1989. The Structure of Ill-structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving. *In:* L. GASSER and M. N. HUHNS (eds.), *Distributed Artificial Intelligence, Volume II*. San Francisco: Morgan Kaufmann, pp. 37–54.

Figure 3, Fidelity Prototyping Workshop (i) wiring things up (ii) a completed prototype (digital loo) site were later supplemented by a detailed transcription of the video recordings. As well as these formally recorded workshops we have also used hands-on group discussions and exercises at a number of other master-classes, tutorials and seminars yielding informal observations.

The Physicality 2007 design exercise has been analysed in greatest detail and reported at the 2008 Design Research Society Conference.[45] Small groups of participants were each given one kit of design materials to use, either paper and pencils, card and glue, or modelling clay, and were only supposed to use their own materials (although some cheated!). They were not told how to use the materials, but the materials implicitly suggested ways of use; for example, no team in the paper and pencil group chose to fold or mould the paper to make a model. In normal design, a designer would chose materials, but in this exercise they had no choices, making this similar to a 'breaching experiment',[56] deliberately disrupting human activities in order to bring to light the tacit or taken-for-granted.

The transcript data was first analysed informally, then subjected to a more systematic in-depth iterative analysis leading to the topics depicted in Figure 5. Our analysis technique was essentially inductive, but driven by initial concerns; for example, a starting hypothesis was that physical materials would lead to more creative results. To avoid blinkered results, we used dialectic recoding,[57] which involves (i) looking for items in the transcript falling outside existing concepts, thus extending our conceptual vocabulary, and (ii) when a transcript item can be coded using existing concepts, asking whether it was 'just' or 'nothing but' what the coding suggested, thus sensing the dialectic tension and suggesting refinements.

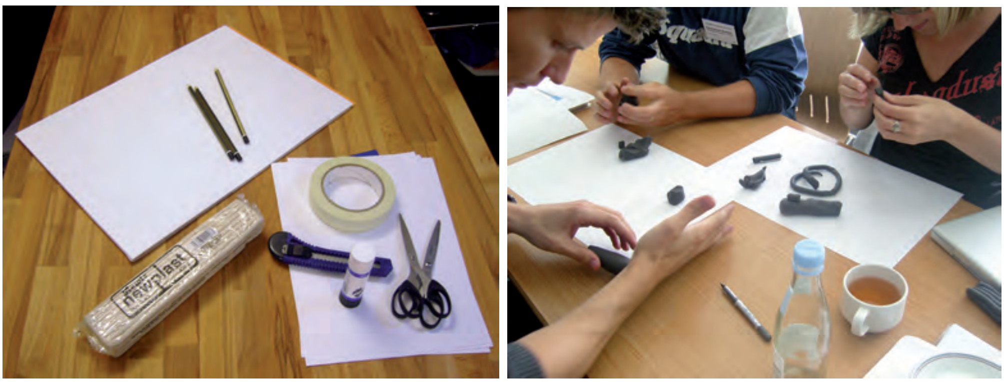


Figure 4, Physicality 2009 Group Exercise (i) materials (ii) clay group at work

[52] DIX, A., 2008. Externalisation – how writing changes thinking. *Interfaces,* 76, pp. 18–19.

[53] REED, M., 2009. Prototyping Digital Clay as an Active Material. *In: Proceedings of the 3rd International Conference on Tangible and Embedded Interaction, Cambridge, 16–18 February 2009*. New York: ACM Press, pp. 339–342.

[54] PHYSICALITY. Available at: <http://www.physicality.org/>.

[55] PHYSICALITY. Available at: <http://www.physicality.org/Fidelity/>.

[56] GARFINKEL, H., 1967. *Studies in Ethnomethodology.* Englewood Cliffs, NJ: Prentice-Hall.

[57] DIX, A., 2008. Theoretical Analysis and Theory Creation. *In:* P. CAIRNS and A. COX (eds.), *Research Methods for Human-Computer Interaction*. Cambridge: Cambridge University Press, pp. 175–195.

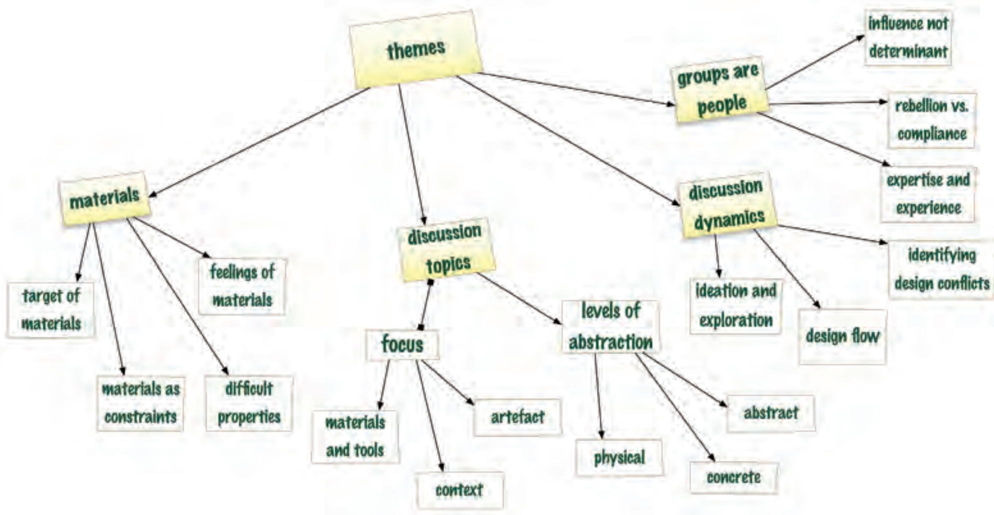


Figure 5, Topics identified during inductive analysis

Laboratory experiments

Throughout DEPtH the team constantly trialled and tested their ideas and methods through practical exercises and experiments.

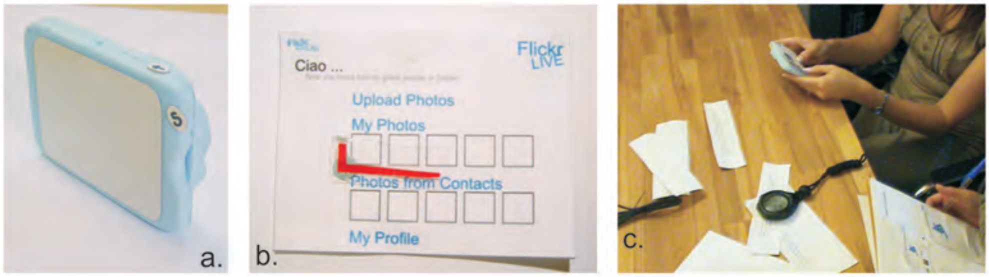
The earliest and most heavily studied of these were the *Equinox* Trials. Three comparative user trials were staged based on an existing home phone product called the BT *Equinox*. The first set of tests compared the real product with a prototype mocked up using the *IE System* and a screen-based prototype. Two further trials repeated the experiment with reduced fidelity levels in the *IE* prototype to determine the importance of physicality. The resulting empirical data showed that the *IE System* produced a more accurate representation of hand held products than a screen-based software prototype. More surprising was that the gains continued even if fidelity levels were significantly reduced.

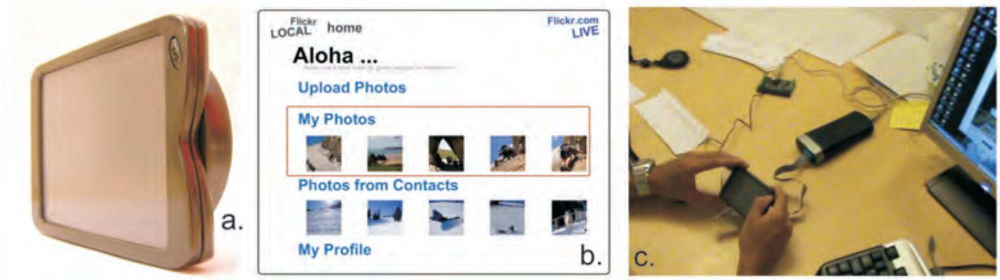
There was an unexpected finding. In a few tasks, users performed better with the lowest fidelity prototype than with the 'better' ones. This prototype had as a front face a flat sheet of printed paper under which were physical buttons. Unfortunately the user could not *feel* the buttons very well, leading to generally low performance, either missing buttons or accidentally pressing neighbouring ones. However, the on/off button was very small and the stiffness of the paper meant that this effectively expanded the pressable region leading to better performance than even the real product.

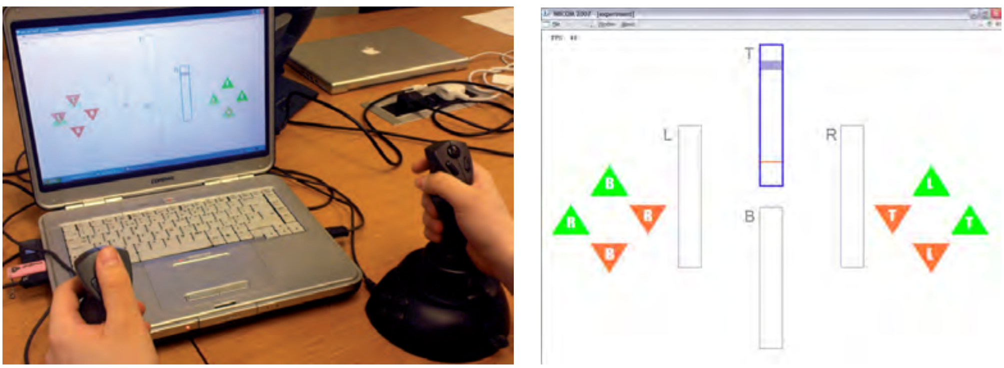
Figure 6, Equinox study (i) different prototypes (ii) during an experiment

These subtle issues affecting performance led the team to explore further appropriate levels of fidelity in physical prototypes. The result was a set of user trials on a conceptual product called the *Flickr Friend*. Three prototypes were built to a single brief within a fixed time, time being the most important driver dictating fidelity levels in prototypes. The initial hypothesis was that fidelity would have a substantial effect on usability. In fact, all prototypes achieved similar results in performance tests. However, users of the mid- and highest-level prototypes, with real time tactile and digital (on screen) feedback, had fewer problems in locating the appropriate interface element. However, they had more problems with their mental model early in the test, whereas users of the lowest level prototype encountered these issues later. It seems likely that users of the lowest level prototype were so distracted by not locating the appropriate interface element that this overshadowed their understanding of the device. The *Flickr Friend* trials gave interesting results but also gave rise to many questions – the effects of physicality are indeed complex and subtle.

A further experiment tested the 'natural inverse' principle suggested by earlier studies. Certain physical actions are the opposite of each other: push vs. pull, lift up vs. press down, turn left vs. turn right. When a device exploits this concept, the user can often use the device even when they do not fully understand the device 'mapping'; for example, you may not know which way to turn the volume knob in a HiFi to make the music louder, but if you start to turn it the wrong way you notice immediately and *without thinking* turn it the other way. In real products many factors operate at once so, in order to separate out factors, we deliberately created a very artificial situation using two joysticks to control four on-screen sliders, measuring user reactions down to 10ms [Figure 9]. This included some mappings that were deliberately easy to learn (good cognitive), and others that were difficult to learn but obeyed the natural inverse







Figures 7, 8 and 9,
top to bottom

Figure 7, Flickr Friend lowest fidelity prototype

Figure 8, Flicker Friend high-fidelity prototype

Figure 9, Joystick experiment

(good physical). We expect the good cognitive mappings to behave well when the user first starts an action as they can easily work out what to do, and the good physical mappings to behave best when the slider 'overshoots' and a correcting action is needed. Full results are not yet available, but early indications appear to support our expectations.

Formal Modelling and Notation

The pre-existing work on natural interaction was partly descriptive, but also used state-transition networks to model the physical properties of a device 'unplugged' alongside its digital or other electronic properties. For example, a light switch can be manipulated physically (push switch up/down), even if not connected to an actual light. This analysis was extended and the notation enhanced, for example, to enable us to describe the way some switches 'give' a little just before they flick, thus allowing the user to try out potential physical interactions without them having an effect. The resulting diagrams were called 'physigrams'. The notation was validated internally by rigorous formal semantics, and externally through the third reflective investigation (*physigrams in design*). The UWIC design team took the notation with only a brief description of use and applied it to the *rotary prototypes* produced by the previous reflective investigation. The adaptations developed by the designers in addressing a real problem have fed back into the notation, which has subsequently been used in a number of tutorials.

An interdisciplinary journey

The breadth of methods adopted is reflected in the publication venues, including the Design Research Society Conference,[45] Formal Aspects of Computing[41] and the International Journal of Arts and Technology.[58] The mix was not entirely as we expected; some methods we planned (for example, workshops), some had not been used as expected (for example, ethnographies of designers at work), and some emerged during the project (for example, workshops *as sources of rich data*). The different techniques address different issues, but together triangulate over the broad topic from radically different standpoints – resisting attempts to over-simplify, whilst at the same time offering detailed analysis on specific points. They are interconnected; reflective investigations feed into workshop exercises, and past literature and experience feeds into formal analysis, which is validated and refined by reflective investigations. We seek to use techniques wholeheartedly within their own remit and thread together the resulting insight, and we eschew prejudices that dichotomise between formal and informal, laboratory vs. wild, qualitative vs. quantitative, even holistic vs. reductionist, as true insight often lies in the interstices of dichotomy.

[58] GILL, S., et al., 2008. Rapid development of tangible interactive appliances: achieving the fidelity/time balance. *International Journal of Arts and Technology: Special Issue on Tangible and Embedded Interaction*, 1(3/4), pp. 309–331.

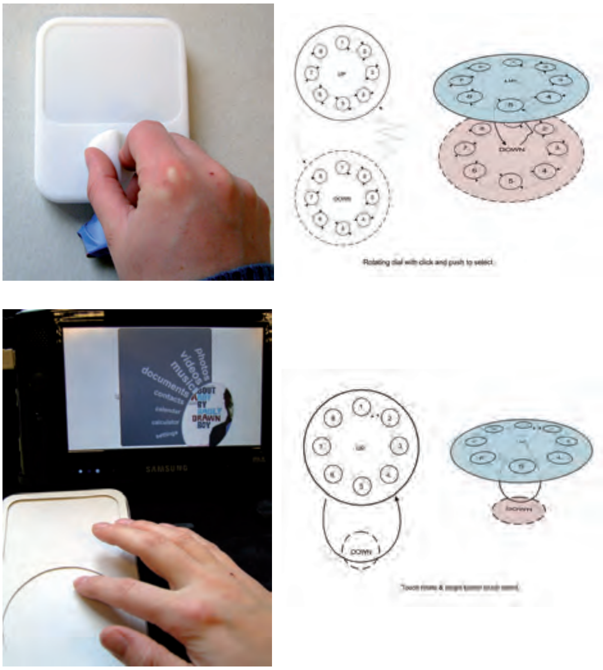


Figure 10, Physigrams in action

New Knowledge and Understanding

Given the range of techniques, we have found detailed results across a number of areas. Here are some examples to illustrate this.

As expected, the *Equinox* prototypes showed that a handheld prototype performed better than a purely screen prototype; these results ran counter to Sharp's simulation studies,[59] probably because the product in Sharp's case (a microwave) was so well suited to a touch screen simulation. Unexpectedly, dropping the fidelity of the handheld prototype had little effect until physical buttons were replaced with a flat (although still depressible) surface.[58] While our focus was prototyping fidelity in the design process, given the move to touch-based interactions and keyboard-less phones, the results do call into question the impact on usability. The way the deformable surface had a positive effect on the small on/off button also emphasises how a fine choice of physical materials intimately interacts with use.

[59] SHARP, J., 1998. *Interaction Design for Electronic Products Using Virtual Simulations.* PhD thesis, Brunel University.

[60] TREADAWAY, C., 2009. Translating experience. *Interacting with Computers, Special Issue on Physicality and Interaction*, 21(1–2), pp. 88–94.

[61] ORMEROD, T., MACGREGOR, J. and CHRONICLE, E., 2002. Dynamics and constraints in insight problem solving. *Journal of Experimental Psychology,* 28(4), pp. 791–799.

[62] BUXTON, B., 2007. *Sketching User Experiences: Getting the Design Right and the Right Design*. San Francisco: Morgan Kaufmann.

In the *Flickr-friend* trials, physicality effects were more complex proving that deeper analysis is required. Qualitative analysis showed that prototypes with real time interaction gave a more realistic user experience and generated more useful comments,[46] while very low fidelity prototyping allows initial exploration of a design idea. However, immediate feedback is essential for deeper studies.

Both the torch project and the Physicality 2007 design exercises revealed subtle *influences* of physical material on design.[45] The torch project revealed the functional/organic differences in design outputs, corroborating different outcomes of hand processes and CAD found by Treadaway in textile design.[60] Materials also impact the group design *process*, for example, breadth (paper and pencil) vs. depth (physical materials) during concept formation. Materials may constrain, but also suggest ideas (rolling of paper, deformability of clay), reflecting the importance of constraints in the creativity literature.[61] Note that we carefully use the word 'influence'; materials *do not determine* outcomes. For example, one group given physical materials 'cheated' and used paper and pencil to sketch, reflecting Buxton's focus on the importance in early design of the indeterminacy of the sketch.[62] Human ingenuity can conquer the obstinacy of the material world; within a single group making a teddy bear model, card was treated as clay (scrunched up skinned with sticky tape), as a flat two dimensional cut out and as textile to form a three dimensional model, tailored by a team member with a fashion background.

Physigrams, their formal semantics, their use in reflective investigation and in formal experiments, have all increased our understanding of natural interaction,[41] enabling clear design guidelines such as the effective use of the 'natural inverse'. The work also foregrounds issues such as the importance of the tiny 'give' of a physical switch, extending and elucidating Gaver's nascent concept of sequential affordance.[35]

Taking a broader view we can see from these examples that DEPtH has contributed to *design principles and practice* in terms of (i) the understanding of the role of physicality in design; (ii) flexible fidelity prototyping including both digital and physical interactions; and (iii) bringing to attention the interactional potential and influence of the physical device prior to it being hybrid (the device unplugged). DEPtH has also engaged with HCI and interaction theory, in particular

[63] GALLAGHER, S., 2005. *How the Body Shapes the Mind*. Oxford: Clarendon Press.

[64] GEDENRYD, H., 1998. *How Designers Work – Making Sense of Authentic Cognitive Activities*. PhD thesis, Lund University, Sweden.

[65] SCHÖN, D., 1983. *The Reflective Practitioner: How Professionals Think in Action*. London: Temple Smith.

creating formal models and notation based on (iii), and doing so with a rigour suitable for formal venues in computing. DEPtH has also been instrumental in nurturing a nascent and *radically interdisciplinary research community* focused on issues of physicality. So while product design of physical form and interaction design of digital behaviour have been largely separate, DEPtH has brought them together at leves of prototyping, human interaction and formal analysis.

In terms of *design and interaction theory and philosophy*, DEPtH to some extent fits within a growing body of work that emphasises the embodied nature of human experience, building on strands from Gibson to Clark. Our work in many ways further emphasises the visceral nature of much of our interaction with the world, including empirical studies of this (for example, the natural inverse Joystick experiments). Both our studies of products and the preliminary results of this emphasise what Gallagher[63] calls *prenoetic* reactions, that is those resulting from mental activity that are not available to conscious examination, so strengthening the evidential basis for this philosophical position. However, our open empirical stance has also challenged the pure enactivist position. In the *Design Journal* paper[42] analysing the group design exercises we found our results contradicted Gedenryd's application of this strand of thinking to design,[64] which claimed that 'designers go out of their way to avoid intramental thinking'. In our own studies we found this sometimes to be the case, but at other times the teams turned to discussion or paper and pencil for more abstract 'stepping back', or as one participant put it '*shapes that our minds had formed in our head*'. This then led to looking afresh at Gedenryd's analysis of Schön's[65] transcripts of dialogue and sketching between an architectural design tutor and novice, and found similar 'stepping back' moments expressed primarily in words. Clark applies a parsimony principle:

'*In general evolved creatures will neither store nor process information in costly ways when they can use the structure of the environment and their operations on it as a convenient stand-in for the information-processing operations concerned*.'[40]

However, we are seeing this parsimony cuts both ways and designers equally do not enact concepts or ideas that are more conveniently and efficiently considered and conveyed verbally or in words. Physicality is an immediate, powerful and a pervading part of our lives, but explicit reflection and analysis are also very real and very important.

DEPtH's purpose was to collate and construct fundamental understanding of the nature of physicality: how humans experience, manipulate, react and reason about 'real' physical things; and, by doing this, to offer constructive guidance to inform the future design of innovative products.

This has the potential to impact designers creating products involving digital aspects that supplement, substitute, modify or subsume the 'normal' physical attributes of the artefact. Ultimately, better products will improve the lives of ordinary users. In addition, community development through workshops and theoretical knowledge through publications has, we hope, benefited academics in product and interaction design and ubiquitous computing, and also touched areas of cognitive, social and philosophical interest. The TouchIT book will complete this picture, giving a comprehensive overview of this rich and cross-disciplinary area, and also exposing the issues to a broader readership.

DEPtH has been an exciting and enjoyable journey; we hope that it has benefitted others as much as it has enriched us.

Additional Reading

DIX, A., et al., 2004. *Human Computer Interaction, 3rd ed*. London: Pearson Prentice-Hall.

MOGGRIDGE, B., 2007. *Designing Interactions.* Cambridge, MA: MIT Press.

NORMAN, D., 2002. *The Design of Everyday Things*. New York: Basic Books.