Active and passive physicality: making the most of low fidelity physical interactive prototypes

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Biographical notes

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Jo has been an RA on the AHRC/EPSRC funded ‘Designing for Physicality’ project investigating the impact of physicality on product design - how humans experience, manipulate, react and reason about ‘real’ physical things, and how this understanding can inform the future design of innovative products.

She has published in journals and conference proceedings, co-edited the ‘Special Issue on Physicality and Interaction’ in the Interacting with Computers Journal and co-organised workshops including two of the ‘International Workshop on Physicality’ series. Jo is currently researching for her PhD “The importance of physicality in the design of computer embedded products”.

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Professor Gill has played an active role in the design research community for many years. He is a member of the Design Research Society and a recent member of the AHRC’s Peer Review College. He frequently reviews for the Design Journal and Interacting with Computers Journal (which he has previously guest edited) and also for a series of high profile conferences including Computing Human Interaction and Tangible and Embedded Interaction. His funding record includes a major Research Council grants and he has collaborated widely with high profile academics, notably Prof. Alan Dix of Birmingham University with who he is co-authoring a book on the importance of physicality in the design of computer embedded products. In recent years he has given invited talks and keynote, notably in Germany and Japan.

Gareth Loudon is a Principal Lecturer in Product Design at the Cardiff School of Art and Design and co-founder and Director of the Centre for Creativity Ltd. that undertakes research, training and consultancy in key areas of creativity. His research interests focus on creativity and the product innovation process, combining ideas from anthropology and psychology, engineering and design. He has over 25 years’ experience in academic and industrial research and has taken several research ideas all the way through to commercial products for large companies such as Apple Computer. Gareth has several patents to his name and over 40 publications in total. Gareth is a Chartered Engineer, a Fellow of the Institution of Engineering and Technology and a Fellow of the Higher Education Academy.

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Abstract
This paper presents three case-studies which comprise a systematic investigation into the use of low fidelity physical interactive prototyping techniques to form a design principle based on the constructs of active and passive physicality. It proposes that, with a better understanding of active and passive physicality, designers can make more effective prototypes for early stage user trials. Results of our studies indicate that the most effective prototypes balance both active and passive physicality equally. In addition, the notion of physicality can demonstrate why, in our studies; paper prototyping, screen-based prototypes and even Arduino prototypes produced unsatisfactory user data.

Keywords
Physicality, fidelity, prototypes, interactive prototypes, computer embedded devices, user testing, usability, human computer interaction, industrial design.

Introduction
This research brings together knowledge from a variety of disciplines to apply them specifically to the construction of physical interactive prototypes of computer embedded devices. Computers have been embedded in our products for nearly half a century, and with an ever evolving stream of new technology, computer embedded devices are a fast-paced topic but this research draws on the essence of the designed object and rises above the latest technology in order to explore physicality at a fundamental level.
The inclusion of an ‘invisible’ computer in computer embedded devices requires electronic interpretation of our interactions for any output. This electronic interpretation can ‘violate’ the basic principles of physical objects (Ghazali & Dix, 2005) and does not have to conform to our experience of the physical world. Computer embedded devices represent an interesting challenge for designers; typically the physical product is designed by an Industrial (or Product) Designer while the software interface is the domain of the Human-Computer Interaction (HCI) specialist. Both these disciplines, although obviously interdependent, are historically very different resulting in a lack of coherence in our computer embedded devices (Overbeeke, 2013).

An iterative design process is considered an effective design process (Rubin & Chisnell, 2008). This approach advocates rapid iterative user testing through inter alia usability trials (Nielsen, 1993), semi-structured interviews (Sharp, Rogers, & Preece, 2007), and expert reviews (Molich & Jeffries, 2003). Low fidelity prototypes are a fundamental tool for many of these techniques, and interactive prototypes can be used to explore the digital considerations within the physical form of computer embedded devices.

It is these low fidelity interactive prototypes, fundamental to the iterative design process, which this research focuses on. By ensuring these prototypes are effective during studies the design team can make better design decisions and thus more usable products.

**Fidelity**

When creating a prototype, the designer needs to balance the visual and functional needs of the prototype, the environment within which it needs to operate (for example, user trials, demonstration, or talk through), and the skills and resources of the prototype team (time and equipment). This balance will have significant impact on the fidelity of the prototype.

Virzi *et al.* (1989) describe fidelity as being "a measure of how authentic or realistic a prototype appears to the user when it is compared to the actual service". Rudd *et al.* (1996) characterize low fidelity prototypes as “limited function, limited interaction prototyping efforts [...] constructed for illustrating concepts, design alternatives and screen layouts”. The authors continue by defining high fidelity prototypes as being ‘fully interactive’ meaning that a user can “interact with the user interface as though it is a real product.” Nilsson & Siponen (2006) propose that fidelity can be defined by the response of the prototype, from fully automatic (user-driven) to non-automatic (facilitator driven). McCurdy *et al.* (2006) proposed five ‘dimensions’ of fidelity that can be defined as somewhere between high and low within the same prototype, namely, aesthetics, depth of functionality, breadth of functionality, richness of data and richness of interactivity.

When designing computer embedded devices, physical prototypes are required that incorporate the digital interaction. Prototypes have traditionally been referred to by their fidelity, yet research into fidelity has been predominantly on software only prototypes (McCurdy, Connors, Pyrzak, Kanefsky, & Vera, 2006), (Nielsen, 1993), (Rudd, Stern, & Isensee, 1996). Of the research that does focus on physical interactive prototypes, the construction of the physical prototype is rarely typical of the product design process. For example; Lim *et al.* (2008) use a real mobile phone and vary the level of fidelity of the on-screen interaction; Virzi *et al.* (1996) use a paper keyboard but not a physical model for their electronic book and Sauer *et al.* (2010) overlaid a cardboard mock-up over the real appliance.

Our research set out to determine if a better understanding of physicality could provide the means of creating prototypes which are effective at eliciting meaningful comments and insights during early stage user trials. We define ‘meaningful’ comments as those that focus on improving the overall intended design of the concept as opposed to the interface in isolation or the construction technique of the prototype.
**Physicality**

Physicality is central to our experience of computer embedded devices, from how we exist in our bodies within the physical world, to how we perceive interactions with the physical world, and the point at which we interact with that physical world. Literature points towards three philosophical discussion areas related to physicality and the designed object; humans as physical beings within our physical world (embodiment and phenomenology) (Clarke, 1998) (Dourish, 2001) (Merleau-Ponty, 1945) (Haugeland, 1998), perception of interaction through physical signifiers (affordances) (Gibson, 1979) (Norman D., 1988) (McGrenere & Ho, 2000) (Gaver, 1991) and at the point at which the digital and physical meet (interaction) (Ghazali & Dix, 2005) (Dourish, 2001). Thus, we define physicality as the physical aspects or qualities of both an object and its interaction; this includes our physical bodies in relation to that object.

**The constructs of active and passive physicality**

We propose that the physicality of a prototype can be considered on two levels; that of active and passive physicality where; passive physicality is the perceived affordance based on the visual appearance and tangibility of the prototype, and active physicality is the perceptible experience of interacting with the prototype.

To explain these terms a useful starting point is that of Dix et al. (2009), who regard a physical device removed from its context, and ‘separated’ from its digital operation, in order to consider the mapping of the device ‘unplugged’. This is the basis of ‘passive’ physicality; the judgments that can be made about a device by considering both its visual appearance and its tangibility (by touching it), without switching it on.

Assumptions are formed about the physicality of the device based purely on its visual appearance as Reeves (2006) demonstrates by asking; do you grasp a cup by its handle or by the body? Decisions are made about the comfort of the cup’s handle by its appearance and the perceived weight of the contents of the cup. The tangible nature of the prototype is also a key aspect of passive physicality; this includes the way the device feels in your hand, its weight, the location of any interactions and surface finish.

Passive physicality also has its roots in Norman’s definition of affordances (Norman, 1988). Affordances suggest ways of interaction which are dependent on the user’s ability to perceive it. The intended design of the device has affordances; in addition, the way in which the prototype is constructed brings its own, different, affordances that affect the way in which the user perceives the prototype. If the prototyping technique used interferes with the user’s ability to make a mental model of how the prototype is operated this will impact passive physicality. For example, if interactions are ‘hidden’ by the physical prototyping method, users cannot perceive that an interaction is possible. Passive physicality forces the designer to recognise that the way in which the physical prototype is executed has an impact on the user’s experience of that prototype.

Active physicality is concerned with the physical act of interacting with a prototype in its ‘on’ state which thus requires electronic interpretation of the action resulting in feedback that can be perceived. Tangible feedback comes from the ‘feel’ of the interaction, whether it is the simple ‘bounce-back’ of a button or electronically enhanced haptic feedback. This interaction will cause the electronic state of the device to change perceptibly, for example a screen change, a light coming on or a mechanism engaging.

The boundary between active and passive physicality is the point at which manipulation of the device occurs which requires electronic interpretation or mechanical action (or both). For example, we use our sense of touch to determine whether buttons fall in a ‘natural’ location (passive physicality) but if we then interact with those buttons to determine what they do and how they feel, this now falls under active physicality. If those actions are intended to initiate further actions, for
example changing a screen element, this should be considered alongside its tactile feedback. An interaction which does not comprise all of its intended actions will have lower active physicality than one that does. For example, if a switch is not connected it will deform and feel like it should but it will not result in any feedback beyond the tactile.

We propose that both active and passive physicality can be considered on a scale of low to high (Figure 1). Our case studies suggest that prototypes which fall below certain levels of either active or passive physicality in relation to the design intent are least effective, and prototypes that balance active and passive physicality equally are the most effective. In this situation an ‘effective’ prototype is one which elicits feedback related to the intended design to enable the next iteration of the design to take place.

The proposal that active and passive physicality should be ‘balanced’ recognises that many prototyping construction techniques require a compromise of some kind. For example, the use of electronics within a prototype necessitates components and power requirements which could impact the size of the prototype and the demand for a highly realistic prototype could impact the way in which the prototype can be interacted with. In these scenarios the resultant physicality of the prototype is affected even though its fidelity is not necessarily altered, without an understanding of this affect any prototype created could be limited in its effectiveness.

The design of these case studies was based on two independent variables; the design of the device and the structure of the trials. In each study the prototypes were constructed of the same design intent with the same functions and features and each prototype within the study was trialled in an identical manner. In addition, each of the case studies had a specific independent variable which determined prototype construction, these were; physicality levels for the media player (case study 1), decreasing fidelity levels for the home phone (case study 2) and time limitations for the photo management device (case study 3). The resultant prototypes were dependent on these parameters and the impact on physicality could then be assessed. Once physicality levels have been determined and the prototypes have been trialled with a consistent structure, any differences in the results of the user trials can be compared in relation to the physicality of the prototype.

**Case study 1 – media player**

In this study, the technique used to construct the four prototypes was determined by our proposed definition of active and passive physicality (Hare, Gill, Loudon, & Lewis, 2013). The intention was to
include the four permutations of active and passive physicality levels as demonstrated by each quadrant of Figure 1. Subsequently, this case study provides an illustrative example of active and passive physicality.

**The prototypes**

An existing media player was chosen as the basis for the construction of four prototypes. A single interface was coded in Adobe Flash for all prototypes and adapted to the needs of each. Preparatory work ensured that this interface would be suitable for all prototypes and that the adaptation of the interface was possible for all. The prototypes are shown in Figure 2.

The ‘blue foam’ prototype was constructed from model-making foam. Interaction was based on the Wizard of Oz technique (Maudsley, Greenberg, & Mander, 1993), the interface was operated remotely by the facilitator, the participant was asked to follow the ‘think out loud’ protocol (Gould & Lewis, 1983), the facilitator could react to what the participant was saying and interacting with on the foam prototype. *Construction time: 6 days 2 hours.*

The ‘white model’ was constructed using rapid prototyping techniques; it was very similar in size and shape to the final device. The buttons and the dial were integrated to make the prototype interactive. An IE4 (Gill, 2013) was used to connect the buttons to a laptop. The Flash interface, shown on a tablet, ‘listens’ for key presses from the IE4 and triggers changes in the interface when the participant interacts with the prototype. *Construction time: 10 days 2 hours.*

The ‘appearance model’ was intended to reflect the final appearance of the device as accurately as possible. The form was constructed using rapid prototyping techniques and finished to facsimile level. The Flash interface was operated by the participant on a separate touch screen tablet. *Construction time: 10 days.*

An approximate foam model was constructed for the ‘foam model with wires’ to accommodate the off-the-shelf buttons and dial. The dial was connected to an Arduino (Burleson, Jensen, Raaschou, & Frohold, 2007) which received the analogue signals and sent them to the computer running the Flash interface. The buttons were connected to an IE4. Due to the extra code required for the Arduino, the interface was shown on a laptop. *Construction time: 8 days 6 hours.*

![Figure 2: Overview of the Media Player prototypes (case study one)](image-url)
Assessing Physicality

The levels of physicality are shown in Figure 3. The tangible and visual qualities of the blue foam prototype are accurate but low fidelity (low passive physicality). Interaction is based on the ‘speak out loud’ protocol and operated by the facilitator, buttons are cardboard but the dial does rotate (low active physicality).

The white model was similar to the final device in its form, weight and the location of buttons, therefore this prototype has higher passive physicality than the blue foam prototype. Upon interaction, the haptic and visual feedback is good approximation of the final device, resulting in higher levels of active physicality in relation to the blue foam prototype.

The appearance model was an accurate representation of the final device (high passive physicality). However, the absence of electronics means there was no feedback from the buttons or dial; and the interface was operated on a touch screen separate to the physical prototype resulting in low active physicality. This prototype really brings out the distinction between active and passive physicality because the buttons on the model have good haptic feedback, yet this does not raise the assigned active physicality level significantly because they do not function.

The foam model with wires has an approximate physical model that is clearly modified to accommodate the switches and dial; the wires are very apparent and visually impact the prototype resulting in low passive physicality. Upon interaction, the feedback of the interactions accurately represents the final device (high active physicality).

Results of the user trial

Users were asked to perform five tasks before commenting on the main menu options, this ensured each participant had the same knowledge of the device for a semi-structured interview. The data was analysed to elicit design recommendations for each prototype and these were compared to the final device (Hare, Gill, Loudon, & Lewis, 2013).
Participants using the white model gave good feedback indicative of the final device. Results of the blue foam prototype show that this prototype was less effective at enabling participants to build a mental model of the device resulting in reduced effectiveness of the comments received. Participants struggled to relate the action they were performing on the physical model to what was happening onscreen (active physicality).

Participants using the foam model with wires required more assistance using the prototype. This was a surprise given that this prototype had the highest active physicality levels. Participants seemed to be affected by the wires and appearance of this prototype (its passive physicality) resulting in less meaningful comments. The appearance prototype had the weakest performance; although some interesting comments were received, the comments elicited by this device did not accurately reflect those of the final device.

Case study 2 – mobile home phone
In this study, the technique used to construct the prototypes was determined by fidelity levels. The study set out to discover if results of a user trial with a tangible prototype were more similar to the final product than a software-only prototype, and the subsequent level of fidelity required of this prototype (Gill, et al., 2008). In total, four prototypes were constructed and compared to a final device. This case study demonstrates how an understanding of active and passive physicality has provided a framework by which to better understand unforeseen results.

The prototypes
Four prototypes were constructed; the first two being a high fidelity model and a software-only prototype (mimicking common prototyping practices), and a further two that lowered the level of fidelity of the prototype, these are shown in (Figure 4).

The ‘high fidelity’ prototype was created by connecting an IE unit to buttons in the casing of the final device, the IE unit enabled button presses on the phone to trigger a mock-up of the phone’s interface created in Flash and shown on a laptop. The same Flash interface was used for the ‘software-only’ prototype and operated through a touchscreen laptop. The ‘sketch’ prototype consisted of a blue foam model with basic integrated buttons and sketch graphics within the Flash.
interface. The IE unit was again used to connect the physical model to the computer to operate the interface. A blue foam model was created for the ‘flat-face’ prototype, instead of embedding the buttons into the front of the phone (one of the more time consuming tasks involved in creating the prototype) a paper print out covered the physical buttons; the same sketch Flash interface was used.

Assessing physicality
The physicality levels are shown in Figure 5. The tangible and visual qualities of the physical model of the ‘high fidelity’ prototype are very similar to the final device, with the difference in weight and appearance of the wires (connecting to the IE unit) being the only compromises (high passive physicality). Upon interacting with the prototype, the buttons have the same feel as the final device with the onscreen graphics performing to a high fidelity albeit on a remote screen (high active physicality).

The visual appearance of the ‘sketch’ prototype is very crude but the tangible aspects of scale, form and button location are a good approximation of the final design (low passive physicality). Upon interaction, the buttons have the similar feel as the final device, the onscreen graphics were very crude in appearance but the structure of the interface is identical to the high fidelity prototype (low active physicality).

The scale and form of the ‘flat-face’ prototype are restricted due to the front being removed, the printed visual appearance is reasonable and the buttons appear to be in a good approximate location (passive physicality is marginally lower than the ‘sketch’ prototype). Yet upon interaction it becomes apparent that the ‘hit’ area of the buttons differs from what is visible on the surface, in addition the physical feedback of the buttons was reduced by the paper, the interface was identical to the sketch prototype (active physicality is significantly lower than the ‘sketch’ prototype).

There was no tangible model for the ‘software-only’ prototype; therefore the only concession to passive physicality is a two-dimensional graphical presentation of the design resulting in extremely low passive physicality levels. The interface was identical to the ‘high fidelity’ prototype yet interaction with the interface was vastly different to the final device with no tactile feedback of the device or buttons. This marks a very interesting attribute of active physicality, the lack of a physical device to hold and manipulate has a very marked effect on active physicality levels despite the onscreen interface being considered ‘high fidelity’.

![Figure 5: Assessment of physicality for the home phone prototypes (case study two)](image-url)
Results of the user trial
User trials were conducted utilising the four prototypes and the final device. Users were asked to complete six tasks and the success rate of each task was recorded (Molich & Dumas, 2008) along with the time taken to complete the task. The ‘high fidelity’ prototype produced similar results to the final device, significantly outperforming the ‘software-only’ prototype. The ‘sketch’ prototype was found to perform similarly to the final device. The performance of the ‘flat-face’ prototype however, was significantly reduced. It appeared that the flat face of the prototype did not replicate the true physicality of the product sufficiently, and the result was more user error which produced in slower performance times and worse performance ratings.

The initial publication of this study concluded that it is not the level of fidelity that is important but rather the considerations of tangibility and physicality. It proposed that there was something which was lacking in the physicality of the ‘flat-face’ prototype that prevented it from being an effective prototype. When our hypothesis of active and passive physicality is considered, it becomes apparent that the ‘software-only’ prototype has no passive physicality and little active physicality. What is surprising in this case is that despite the interface being identical to the high fidelity prototype there is a difference in way in which the interface is operated. There is no physical model or buttons with which to operate the interface, and this has a significant impact on the active physicality level because the user cannot tangibly feel the model or interaction.

In this trial, the ‘sketch’ prototype, although low fidelity, implements enough active and passive physicality for the user to understand the design on a similar level to the ‘high fidelity’ prototype. This reveals a significant saving in time and expense in terms of constructing a prototype, in addition to being able to construct this type of prototype earlier in the design process enabling more iterations of the design.

On initial appraisal, the ‘flat-face’ prototype appeared as though it would produce effective results because the only difference between this and the sketch prototype is the paper covering the buttons. But when notions of active and passive physicality are applied, it becomes apparent that active physicality is very low in comparison to the design intent. Feedback of interaction is poor since the participant cannot determine exactly where the ‘hit area’ is underneath the paper, resulting in unsatisfactory feedback upon interaction (active physicality). In addition, it seems that the interactions are not transparent enough for the user to understand how to operate the prototype, in other words, the appearance and tangibility of the prototype suggest there is little the participant can do with the prototype (perceived affordance resulting from passive physicality). This prototype has been a really interesting case study because it seems to marginally challenge the boundaries of an acceptable low fidelity interactive prototype.

Case study 3 – conceptual photo management device
In this study, the technique used to construct three prototypes was determined by allocating time limits during construction. A conceptual device was chosen in order to fully reflect the nature of low fidelity prototyping early in the design process when there are many unresolved aspects of the design. Initial design work was undertaken in order to reach a stage where, in a real design process, an interactive prototype would be the next natural step. Each of the resulting prototypes used this initial design work as the starting point, therefore only the time to construct the prototype differed (Hare, Gill, Loudon, Ramduny-Ellis, & Dix, 2009). This case study further demonstrates how the framework of active and passive physicality can be used to better understand unforeseen results.

The prototypes
Three prototypes were constructed (Figure 6); the considerations that drove the level of fidelity and its effects on the physicality were purely time based, with the allocated times of 4 hours, 14 hours and 5 days.
A blue foam model was created for the ‘low fidelity’ prototype. A series of paper screens were created for the interactions based on the principles of paper prototyping. The prototype required a facilitator to operate the ‘interface’ while the user talked through their interactions. Construction time: 4 hours.

The physical model was created using rapid prototyping techniques for the ‘medium fidelity’ prototype. Buttons were integrated into the physical model and connected to an IE Unit operating a Flash interface displayed on a laptop. Construction time: 14 hours.

The ‘highest fidelity’ prototype was based on the mid-level with the extra time used to give the physical prototype a more realistic visual finish and improve the feel of the interaction. The interface was developed to operate in a smoother manner reflecting the intended design. Construction time: 5 days.

Assessing physicality

The levels of physicality are shown in Figure 7. Although the physical form is relatively accurate for the low fidelity prototype, it feels very lightweight; interactions are clearly depicted but perceptibly non-functional (low passive physicality). Interaction relies on the participant pressing cardboard buttons and talking through their actions with the facilitator interpreting this by adjusting the paper screens. Although buttons are accurately located on the prototype, there is little tactile feedback of the buttons and delayed visual feedback of the interface (very low active physicality).

The physical form factor of the medium fidelity prototype is relatively accurate; the unfinished form and tacked on buttons inform the user that interaction is possible but it does not visually reflect the final device. Therefore the passive physicality of this prototype is low but still higher than the low fidelity model. The dial gives haptic feedback but this is not representative of the intended design; this dial feels ‘clunky’ and cannot rotate 360 degrees whereas the intended design fully rotates giving more subtle haptic feedback. Visual feedback of the interaction is immediate and the interface is functionally accurate but screen animations are not as refined as the intended design, therefore active physicality is higher than the low fidelity model. This example demonstrates the importance of relating the physicality of the prototype to the intended design of the device. In this case the active
physicality of the prototype would have been higher if the intended design had reflected the haptic qualities of the dial mechanism used in the prototype. Yet a more representative dial was known to significantly impact the length of time this prototype would have taken to construct because of the extra coding required as demonstrated by the highest fidelity prototype.

The highest fidelity prototype was constructed and finished to accurately represent the intended design visually and tangibly (high passive physicality). It could be further improved by ensuring the weight of the device is more accurate. The interactions of the device reflect the intended design well with the dial providing full rotation with subtle haptic feedback and the interface includes good visual feedback (high active physicality).

![Diagram](image)

**Figure 7: Assessment of physicality for the photo management concept prototypes (case study three)**

**Results of the user trial**

Users were asked to perform five tasks on the prototypes, task success rate was recorded and discourse analysis was performed on the resulting data. Initial analysis showed that task success rate did not differ significantly across the prototypes, although results suggested that the greatest difficulty for users of the lowest fidelity prototype was identifying the correct interaction; whilst users of the medium and highest fidelity prototypes had more problems creating a ‘mental model’ of the interface. Discourse analysis revealed that the ‘medium’ and ‘high’ level prototypes were more effective at eliciting useful user comments than the ‘low fidelity’ prototype.

When our hypothesis of active and passive physicality is considered, we can see that, despite being of very different fidelity, the physicality of the medium and high fidelity prototypes is relatively similar. Therefore, in terms of physicality, very little has been added to the high fidelity prototype despite the additional time spent creating the prototype. The low fidelity prototype, however, is very low in active physicality due to the lack of haptic and visual feedback of the prototype. Despite setting out to assess the effect of physicality, when the notions of active and passive physicality are applied the prototypes used in this study are fairly similar. This could explain why the results of this study were inconclusive.
Discussion
In total, eleven prototypes of three separate products were studied. The relative success of each prototype can be approximately determined by comparing the data the prototype produced during user trials to the other prototypes in that case study. Figure 8 shows the relative success of the prototype versus the time taken to create the prototype (for study two these are approximate times).

Prototypes without embedded electronics
The ‘software-only’ prototype of study two took the least time to create. This prototype had no physicality, although it could be argued that there is some physicality if the intended device is touchscreen and it is prototyped on a touchscreen. However, this was not the case in our study and the inclusion of an ‘appearance’ model can be used to address this. Our ‘appearance’ prototype (study three) was close to the design intent for passive physicality but active physicality remained low. Previously, it was thought that the inclusion of an ‘appearance’ model was adequate to inform the design process, but our studies have demonstrated that these prototypes produced unreliable data compared to the other prototypes in the series. In study one, the interface required between 59% and 96% of prototyping time depending on its level of fidelity. Therefore, with as little as 4% extra time, the effectiveness of the prototype can be greatly improved by the inclusion of an interactive physical model bringing the level of active versus passive physicality into balance.

The effectiveness (or lack thereof) of paper prototyping has been a surprise outcome of these studies. It is a technique used regularly in commercial work, yet study one suggests that the lack of real-time feedback (active physicality) results in a decrease in the quality of results. This prototyping technique is classified as a ‘non-automatic’ by Nilsson and Siponen (2006) because the facilitator plays a very noticeable role in the eyes of the participant. The reduction in the quality of data was thought to be due to the delay of the facilitator in updating the interface and the inability to ‘explore’ the interface because of the added ‘unnecessary’ work the participant felt they were causing the facilitator (Sefelin, Tscheligi, & Giller, 2003). Indeed, Nielsen (1990) found a similar result where users found significantly less ‘global’ problems when using a paper prototype compared to a
software prototype. Yet paper prototyping has been proven to be a successful method for usability studies (Snyder, 2003) (Sefelin, Tscheligi, & Giller, 2003). The user trials of study three were designed to obtain feedback about the scope of the overall design (what Nielsen describes as ‘global’ considerations) rather than task structure. Paper prototyping seems to be more appropriate when exploring the more detailed information architecture of an interface. Perhaps this suggests a lower limit of active physicality; the prototype should appear to be ‘automatic’, or real-time, for early stage user feedback based on usability trials.

Study one addressed the lack of active physicality in the paper prototype through the ‘blue foam’ prototype; this increased levels of active physicality through the facilitator operating an ‘automatic’ interface thus balancing the levels of active and passive physicality. This ‘blue foam’ prototype proved successful in eliciting reliable user feedback; the higher fidelity ‘white model’ outperformed this foam prototype but as a quick and dirty prototype this ‘blue foam’ prototype was a success.

The ‘appearance’ prototype of study one posed an interesting question in relation to the buttons. On this prototype the buttons felt similar to the end device but they were not functional. Active physicality has been proposed to be the perceptible feedback of interacting with the device; and, haptically at least, the interactions are accurate. Yet these interactions do not trigger any other feedback, so the user is not able to relate their interactions to the product as a whole.

‘Smart’ prototypes
The inclusion of electronics within the prototype is a common way to increase the fidelity of interactive prototypes; this enables real-time interaction and an improved richness of interactivity (impacting active physicality). Seven of our prototypes covered a variety of approaches to making the prototype ‘smarter’. Some of those approaches have resulted in an adjustment to the physical form and some have resulted in additional wires being present; in all of the prototypes studied, the screen was outside the physical model. Studies one and two demonstrate that the remote screen had no impact on the data gathered by comparing results to the final device with integrated screen. This allows a significant reduction of the development time of prototypes pushing levels of fidelity and physicality even lower. The prototypes that had a significant impact on passive physicality produced the least reliable data, the two extreme cases in our studies were the ‘flat-face’ prototype of study two and the ‘foam model with wires’ of study one. The physical form of the ‘foam model with wires’ was distorted due to the size of the switches and dial used, in addition, the wires and prototyping board were clearly visible impacting passive physicality. Participants commented that they felt ‘intimidated’ by the appearance of the electronics and that interactions were not easy to reach on the prototype. The ‘flat-face’ prototype used in study two had a paper cut-out covering the buttons to avoid the need to embed the buttons in the front of the model, saving a few hours’ work. The effect of this paper cut-out was two-fold; firstly the level of passive physicality was too low because the ‘hit-area’ shown on the paper cut out was not the true hit area of the buttons beneath it, and secondly, upon interacting with the device (active physicality) the paper and misalignment of hit-areas caused inadequate feedback.

Balancing Physicality
In our studies, the most successful prototypes balanced both active and passive physicality equally, these included the very low fidelity ‘sketch’ prototype and ‘high fidelity’ prototype of study two, the low fidelity ‘blue foam’ prototype and the higher fidelity ‘white model’ of study one. The least successful prototypes did not address one, or both, aspects of physicality, these were the ‘software-only’ and ‘flat-face’ prototypes of study two, and the ‘low fidelity’ paper prototype of study three. The remaining prototypes focused too much on either active or passive physicality with less consideration of the other, although these prototypes produced valid data, it was not as reliable as the well-balanced prototypes.
When we relate these notions back to the time taken to create each prototype we can see that the extra time invested in the prototype was perhaps inefficient. For example, the ‘foam model with wires’ and ‘appearance’ models of study one took more time than the ‘white model’ of that same study but were less successful. In order to increase the effectiveness of the ‘appearance’ prototype and ‘foam model with wires’, they could be combined with further investment to source buttons and dials that did not have a significant impact on passive physicality. This type of investment would be more justifiable towards the later stages of the design process.

As was hypothesized in study two, it seems that it is not the level of fidelity that is important in these prototypes. Rather it is considerations about the physicality of the prototype in relation to the design intent, specifically that there is a good balance between active and passive elements of the prototype.

**Conclusion**

We propose that the physicality of the prototype should be considered on two levels; that of active and passive physicality where passive physicality is the perceived affordances based on the visual appearance and tangibility of the prototype and active physicality is the perceptible experience of interacting with the prototype. This notion of active and passive physicality has provided a clearer understanding of the results obtained in our investigations.

Physical interactive prototypes require an electronic prototyping platform, software, interactions (such as button and sliders) and hardware (to run the prototype) within a physical form. Many different prototyping techniques exist that bring together these elements in a variety of ways; the application of active and passive physicality in the planning stage enables prototypes to be executed in the most efficient manner to elicit meaningful comments and insights from user trials. Some of the prototypes presented in this paper push physicality to a level where results were compromised, suggesting that there is a certain level of physicality that prototypes should not fall below. The most successful balanced the levels of active and passive physicality equally. Therefore, resources should not be used exclusively on the prototypes interaction (active physicality) if it severely impacts the ways the prototype looks or can be held by the user (passive physicality). Likewise, resources spent creating a prototype that closely resembles a final device is not effective if interactions are not well supported.

**Future work**

Future work will seek to determine the relevance of passive and active physicality beyond our case studies by evaluating prototypes emerging from both research and commercial projects. Further case studies could focus on different prototyping techniques such as augmented and virtual prototyping plus devices that change shape such as those with flexible screens.

**References**


