Making Sense of Sensors: Discovery Through Craft Practice With an Open-Ended Sensor Material

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ABSTRACT

This paper explores the process by which designers come to terms with an unfamiliar and ambiguous sensor material. Drawing on craft practice and material-driven interaction design, we developed a simple yet flexible sensor technology based on the movement of conductive elements within a magnetic field. Variations in materials and structure give rise to objects which produce a complex time-varying signal in response to physical interaction. Sonifying the signal yields nuanced and intuitive action-sound correspondences which nonetheless defy easy categorisation in terms of conventional types of sensors. We reflect on a craft-based exploration of the material by one of the authors, then report on two workshops with groups of designers of varying background. Through examining the objects produced and the experience of the participants, we explore the tension between tacit and explicit understanding of unfamiliar materials and the ways that material thinking can create new design opportunities.

Author Keywords

Embodiment; Material Exploration; Sensor Technology; Material Improvisation; Craft; Meaning Making

INTRODUCTION

Anthropologist Tim Ingold levels a broad critique of the view of making as a designer imposing a form upon the material world [19]. Rather than viewing matter as a passive and inert substrate to be moulded to one's ends, Ingold prioritises making as *process* of formation in which the material serves as guide. Taking from Deleuze and Guattari the example of the woodsman's axe [12], Ingold notes the woodsman's ability to align his strokes to the grain that is already present in the wood. Generalising, he writes: "Practitioners, I contend, are wanderers, wayfarers, whose skill lies in their ability to find the grain of the world's becoming and to follow its course while bending it to their evolving purpose." Or putting it more simply: "follow the materials" [19].

This is a paper about *grain finding*. Our work emerges out of HCI's "material turn" [33] in which the physical and digital are increasingly intertwined, and material properties are increasingly a source of inspiration, negotiation and influence. Material-driven design processes [23] are increasingly found in HCI [44], where they involve the designer coming to terms with the material, possessing or developing a tacit or explicit understanding of its properties or character. Our research probes *how* designers develop the knowledge that lets them, in Ingold's words, "follow the materials."

In this paper we present a novel open-ended sensor material in which the movement of structures of conductive and non-conductive materials within a magnetic field produces a rich, high-bandwidth signal. Though the sensor's principle of operation relates to other magnetic sensors, its particular behavioural characteristics and the open-endedness of its implementation mean that it defies easy categorisation into familiar categories of sensors (e.g. pressure, position, acceleration, etc.). We first conducted a design inquiry into the character and interactive possibilities of the material, led by one of the authors with a background in material-led design, which we present here in a first-person account. We then present the results of two workshops in which 12 designers of varying technical and material backgrounds produced semi-functional prototype objects based on the sensor material.

That designers are influenced by their materials is a broadly-accepted foundation of design research [34, 23]. In seeking to understand how this influence unfolds, this paper takes an inverse perspective from much of the literature: rather than starting from a established understanding of material properties and querying design implications, this paper explores an unfamiliar sensor composite and seeks to infer its grain retrospectively by observing how designers respond to it in improvisatory explorations. We also investigate the meaning-making processes of the designers themselves, querying the extent to which either a tacit or explicit understanding of the material emerges and the role that pre-existing mental models

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play in shaping this emergent understanding. We frame our results in HCI discourses on ambiguity, craft practice and tacit knowledge, and in metrology (the study of sensors).

BACKGROUND

Material turn in HCI

In attempting to characterise the impact of new computational materials on interaction design, Robles and Wiberg offered the phrase "material turn" to describe a transformative process in which material descriptors such as *texture* can signify relations between "surfaces, structures and forms" across the physical and digital [33]. The ramifications of this reframing of materials in HCI, which aims to encapsulate both physical and digital, have been explored by Barati et al. who describe a "disruption of affordance" caused by "smart material composites" [6]. Reflecting on the design of tangible interfaces, Hornecker similarly notes that designers' capability to design and restrict affordances with hybrid physical-digital objects is limited due to their "potentially endless" use cases [18].

To address these challenges to design, Wiberg comments that "a wide repertoire of methods" are required to fully realise "research through a material lens" [44]. This altered material landscape has led to the prominence of material-driven design (MDD) [23], as a means for designers to embrace continuous novelty and flux. From an MDD perspective, materials "not only enable and constrain action, they also unfold through collaborations" between people and between other materials, in effect "having a say in the process" [34] and "shaping ways of doing and practices" [23].

Under Wiberg's approach to defining material, both physical and digital properties can be considered together as composite materials [45]. Nevertheless the character of these composites often convey greater or lesser emphasis towards physical or digital, which are worth considering in research according to Jung and Stolterman [22]. As an example, Vallgårda's work explores the potential of *programming* in practices engaged with new materials, and the establishment of embodied programming tools and methods that this necessitates [39]. Sundström et al. have similarly argued for the need to make digital material processes visible and tactile for designers, and propose "inspirational bits" as transparent and approachable distillations of digital affordances [38].

Craft-based inquiry in HCI

A complimentary approach to material-driven design is craft-based inquiry [14], which notes that aligning and integrating hybrid crafting techniques and processes, creating highly refined objects, and creating knowledge through deeply embodied engagement, are all in agreement with principles from craft research [24]. This bridge means material-driven practices can be inspired by craft research and vice versa. Kettley for instance emphasises that extending and transforming the definition of material is a common theme in craft practice [24]. Redefining material in this sense does not have to stop at combining physical and digital, but can expand further still to approach people and networks as material if contextually relevant, suggesting that the definition of material itself "unfolds" [34] throughout a process.

Craft-based inquiry holds other benefits for the material turn. Making sensors from "craft materials" [8] and focusing on craftsmanship with technology can lead to more inclusive technology [37], owing to the "value-based" [24] and "person-centric" [25] perspective of craft practice. In addition, craft research increasingly offers deep, longitudinal and sometimes first-hand encounters with materials that can serve as a reference point for new practices with emerging material innovations [31, 5, 26]. Adequately supporting digital handcrafting processes requires stepping back from the technologically-driven desire to produce toolkits of decoupled, perfectly abstracted blocks of pre-defined functionality, since these can constrain authentic craft responses in undesirable ways [32, 46]. Instead, such materials may need to be "un-crafted" [30] and presented to practitioners in more raw and open forms, to allow space for novel concepts to emerge [1, 2].

Exploration in open-ended contexts

To create artefacts that contribute to and harmonise with the environment around them, designers need means for exploring open-ended contexts. Part of this open-endedness may involve a lack of familiarity and ambiguity, and both of these ideas have become themes in recent HCI discourse [15, 36, 42]. When viewed as constructive design resources, de-familiarisation and ambiguity can foster novel and rich exploratory processes, resulting in outcomes that themselves continue to provoke new interpretations.

On the other hand, total novelty and ambiguity risks the failure of a design to communicate appropriately at all. To find a balance, designers also need to seek, invent and play with familiarity in open-ended contexts, identifying both tacit and explicit [10] points of reference to lived experience within novelty and ambiguity, and using them appropriately.

Two possible means for exploring open-ended contexts are bricolage [40] and material improvisation [3]. Bricolage is described by Vallgårda as "in-situ negotiations of concerns from a non-hierarchical perspective" which are naturally predisposed to material design due to their "sensibility towards the unstable physical world" [40]. Andersen et al. note that material experimentation as an "under-described factor" in recent HCI discourse, and that improvisation could help to describe "shifts the focus from outcomes to processes [...] in conversation with materials" [3].

Analog material programming

When considering material-driven design and craft in open-ended contexts, an underappreciated issue where computational technologies are concerned is the manner of representation they rely on. Frequently, such as with tangibles, this is assumed to be digital, which can be problematic due to thier inability to anticipate open-ended contexts [18]. In contrast, Mclean invites us to compare "the internal symbol systems of humans with those of computers", noting several antonyms between analog and digital; "continuous vs. discrete, image vs. language, smooth vs. striated, amorphous vs. pulsating, plane vs. grid, articulation vs. sequence", etc [28]. We propose that, for the issues we are concerned with in this work, analog computing [27] is potentially highly suitable for addressing the

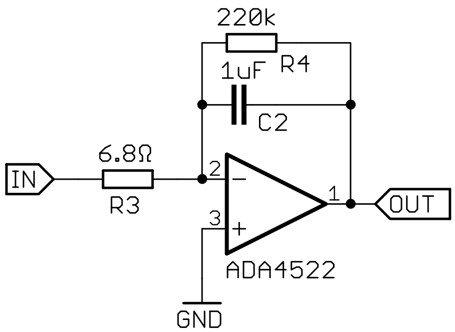

Figure 1. A low-drift integrating amplifier for magnetic signals which provides an approximate measurement of the total quantity of motion.

needs of designers involved in material programming practices [39]. Furthermore, sound and sonification which play an understated role in the designed environment are such mediums which enable analog material improvisation [7, 43].

SENSOR MATERIAL

Principle of Operation

The sensor material used in this study is based on Faraday's Law of magnetic induction, in which a loop of conductive wire moving in a magnetic field will produce an electric voltage proportional to the rate of change in the magnetic flux through the loop. This classical principle underlies nearly all magnetic sensors, from dynamic microphones to electric guitar pickups to phonograph cartridges, not to mention countless other pieces of electrical machinery.

In our usage, the sensor material typically consists of a high-strength neodymium magnet embedded within a structure made of soft, flexible or compressible material into which one or more loops of conductive wire have been embedded, all at the discretion of the designer. In this sense what we refer to as a "sensor material" could actually be composed of many different types of physical materials, a discussion to which we will return at the end of the paper.

Though moving coils and fixed permanent magnets also characterise many magnetic pickups, the novelty in our usage lies in the wide variety of conductive and non-conductive materials from which the sensor can be crafted, and the open-ended way in which a designer can structure the materials to elicit different types of interaction. This open-endedness and sensitivity to human interaction is possible because of the nature of the amplifier, discussed in the following section.

Amplifier and Signal Conditioning

The electrical voltage generated by a moving wire in a magnetic field is proportional to its velocity. For direct manipulation by human hands (as opposed to, say, the vibrations of a plucked string), the velocity will be comparatively small. Moreover, we expect many designs with the sensor material to consist of only a single wire rather than the hundreds or thousands of turns found in conventional pickups. Therefore, a special amplifier topology is needed to amplify the miniscule signal (on the order of microvolts) that results.

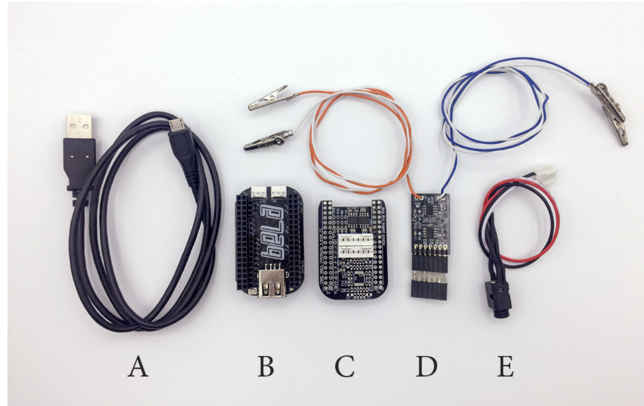

Figure 2. Kit for sonifying the sensor material: (a) USB cable for power; (b) Bela embedded computer; (c-d) preamplifier boards, with crocodile leads in (d) connecting to conductive material; (e) audio cable for headphones or speaker.

Proportional amplification of the signal would provide an output primarily consisting of short transients when the magnet or material move quickly with respect to one another (e.g. strikes, plucks). Most forms of human interaction unfold at slower speed but with longer duration. To detect these motions, Figure 1 presents an inverting leaky integrator with a corner frequency of $(1/2\pi \mathrm{C2R4}) = 0.7\mathrm{Hz}$. By integrating the incoming signal, the output provides an approximate measurement of the total quantity of motion of the wire with respect to the magnet. The ADA4522 zero-drift (chopper) op-amp is chosen for its extremely low input offset voltage (5μV) and low $1/f$ noise, allowing very high gains at low frequencies without being swamped by noise and drift.

That the output of Figure 1 is the integral of the velocity of the wire suggests that it would produce a position measurement. However, both the high-pass filter at 0.7Hz and the nonuniformity of the magnetic field above the pickups mean that the actual signal cannot be precisely characterised this way. This has important consequences for the following explorations, because it means the output of the system resists any well-defined label: depending on the physical configuration of materials, the sensor output might be influenced by position, velocity, quantity of motion, impacts or pressure, but it is not a pure measurement of any of these quantities.

Sonification

The analog signal produced by the sensor and amplifier is capable of full audio bandwidth and substantial dynamic range. In principle, digital analysis of this signal given knowledge of the underlying physical form could extract a great deal of nuance about the user's actions. For this research, we were not interested in information retrieval nor in fully functional prototyping, but rather in material exploration. We therefore settled on an extremely simple sonic feedback system in which the signal was multiplied by a sine wave (typically tuned between 500 and 1000Hz) using a Bela embedded audio processing board [29]. This transposed the low-frequency content of the signal into the audible range, providing low-latency feedback that follows the subtle nuances of how the material is manipulated.

Form and Physical Materials

The kit is shown in Figure 2. The designer connects the two crocodile clips to either end of the wire in their object, whose design is entirely open-ended. Most applications of this sensor principle typically involve a conductive element which can move in particular patterns constrained by a non-conductive substrate. For example, in Figure 3b, a conductive wire is threaded through a crocheted triangle of fabric, such that plucking or mashing the fabric causes the wire to move with respect to a magnet stuck underneath the wooden baseplate.

The conductive element could be an ordinary copper wire of any gauge, but for the design explorations in this paper, we typically turned to a range of conductive materials from e-textiles, including various metallic threads and adhesive metallic tape. Similarly, since we seek to investigate the diversity of ideas developed by our designer-participants, we investigated a wide variety of non-conductive substrates, including various foams, fabrics and paper-based materials, all of which were easily sculpted into different forms.

METHODOLOGY

Our experimentation with this new sensor material was done in three stages. The first was a design exploration done by one of the authors. The second was two workshops with participants from various design backgrounds and the third was a longer-form exploration by four of the participants from the second workshop. The personal design exploration provided a deep understanding of the sensor. This knowledge translated into a series of demonstration examples to be used in the workshop. Additionally, it gave the facilitator expertise to help participants with their designs and informed the material choices for the workshop.

We were interested in discovering how people come to understand and make sense of this new sensor material. In order to achieve this we first had to teach participants how to make their own sensors. This was done through two hands-on workshops where the participants could familiarise themselves with the technology. The longer-form exploration built on the experience gained during the workshop. We thought participants would develop their understanding of the sensor through an extended period of design work. Further, we thought the participants would design differently working in their own environment and with their own choice of materials.

DESIGN EXPLORATION

One of the authors [CN], a material designer, spent several months exploring the sensor material, driven by a desire to understand underlying principle of what the sensor does. Her reflections are presented here in the first person:

Reflections from the Exploration Process

In the beginning, exploration was focused on understanding the different characteristics of the signal. This was done by moving a magnet over a piece of conductive tape in various directions while the preamp was connected to an oscilloscope. The purpose of this exercise was to see that it was in fact possible to produce a signal with this method. Moving the magnet in one direction seem to produce a slightly different result than moving the magnet in the other direction.

Significant thought went into how to visualize the magnetic field in order to make something abstract and intangible visible and, to some extent, tactile. This was achieved in part by using a magnetic viewing film that see the field lines of the magnet in addition to working with a sonified signal.

Alongside these more technical explorations were explorations into thinking about ways of interacting with the sensor material. Through experimentation, I tried to understand what the sensor senses and its underlying principles. Asking myself questions such as whether different stitches and material choices would produce different sounds/signals. A recurring theme in my exploration was how the craft practice could influence the signals.

The second stage of exploration was focused on finding the parameters of the sensor material. By combining different conductive materials and non-conductive materials. These materials included paper, fabric, foam, air-dry ceramic, wood along with various type of conductive thread, conductive tape, wire wool, wire, copper fabric and other conductive fabrics. Through the exploration I found thin lines of conductive material more effective than whole surfaces. Additionally, the relationship between where you interact with the object and the placement of the magnet has an impact on the signal.

I found stitching with conductive thread through open-cell foam produced as sonically strong and reliable signals as more tedious hand-crafting techniques. As it was a lot faster to produce, I took advantage of this to produce a greater variety of forms with these materials.

One of the most interesting sensors created during this process was a piece of foam stitched with conductive thread (Figure 3c). Due to the nature of the stitching's arrangement in three dimensions within the foam, the sensor was responsive in more than one direction. This principle could be simplified even further by running a single conductive thread through the core of the foam piece without a using a particular stitch. Further, this simplified version suggested possibilities of running multiple channels of conductive material in a single piece of foam.

The sensor explorations included probing their ability for richness and nuance. Where I understand richness to mean a richness of gestures - one sensor could have a series of different ways to be interacted with. These interactions would produce slightly different sonic qualities and as a result give a nuanced signal.

In addition to the questions around the material properties and interaction of the sensor I spent time considering what the signal means once it is inside the computer. The sonification of the signal gave me a tangible idea of the signal as some interactions would only produce distant rumbling noises whereas others would make such loud and sharp sounds that I would jump and keep my headphones at a distance from my ears. These sonic qualities gave me an indication that it is possible to elicit more than one type of signal from the same sensor. However, the question of what the signal means still remains.

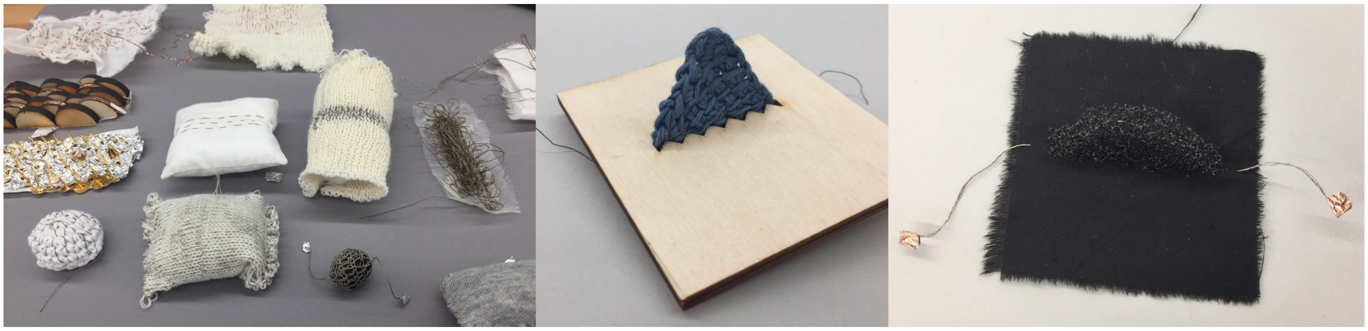

Figure 3. Example sensor objects made by designer-author CN. A permanent magnet is typically mounted underneath or inside each object.

After spending several months exploring the sensor material I still cannot give a clear explanation of what is being sensed. I know that if I make a particular kind of gestural movement it will result in a specific signal. The result is consistent, but not easily described.

WORKSHOPS

Our next step was to discover how other designers came to terms with the sensor material, examining their initial assumptions, modes of experimentation, objects created and reflections on the experience of engaging with the sensor. We undertook this investigation in a workshop context. Two half-day workshops were held, the first with 8 designer-participants (4M, 4F) and the second with 4 designer-participants (4F). Many of the designers were new to working with technology, and the operation of the sensor was unfamiliar to all.

The workshops take a *semi-functional prototyping* approach [4], charting a middle ground between design fiction exercises such as Andersen's *magic machines* [2] in which no electronic technology is used and the behaviour is entirely speculative, and design of fully-functional interactive objects based on sensor toolkits. In the workshops, the literal behaviour of the designed objects would be to produce sound in response to physical manipulating, but the participants were instructed to consider the sound as a stand-in for an imagined interactive behaviour, without worrying about how a digital system might eventually be able to interpret the sensor signals to produce that behaviour.

In each workshop, we sought an account of how the designers crafted objects to make use of the sensor material, their own perceptions of how the sensor material worked, the kinds of physical interactions they felt that it responded to, and the speculative applications to interactive digital systems.

Procedure

Both workshops

Participants began by filling out a background survey asking about their design background and experience, their material preferences and typical outcomes of their work. They were then introduced to the sensor including its basic principle of operation.

Each participant was given a kit containing a Bela and amplifier board with two crocodile leads to connect to the objects being crafted. They were also provided with headphones, various magnets, and one of author's example sensor objects. The examples were chosen for their diversity of material approaches and interactive affordances. The participants were encouraged to pass the example around, trying out various magnet placements to see how they alter the signal. To keep the focus on tactile interaction and auditory response, they were encouraged to interact with eyes closed. After 10-15 minutes of testing, participants were introduced to the available materials, both conductive and non-conductive, and given brief explanations on technical aspects including: electrical conductivity (which differs by material) and the impact it has on the sensor output; magnet shapes and the field lines they produce; basic circuitry: how to produce a closed circuit and avoid short circuits.

Conductive materials available for prototyping included wires of various gauge and metal, adhesive copper tape, copper fabric, and several types of conductive thread. Non-conductive materials included several types of foam, fabric, paper/card and thread. A monochrome grey-black palette was used, partly inspired by Hara's book *White*, where the 'emptiness' of the colour white allows for meanings to stand [17]. Here, the monotone palette was intended to focus the exercise on tactile and sonic qualities rather than visual or decorative aspects.

Following Andersen's advice [2] and Claxton's suggestion that thinking can be a hindrance to performance [9], the main activity consisted of a 'quick and dirty' approach in which participants got a feel for making sensors, aiming to break down barriers to making or interacting with the sensor material. This activity was divided into two sessions. The first part aimed to build familiarity with the materials and technology and start making without thinking too much. The second part was a more focused session where participants had a chance to start again or iterate on the sensor they had already made.

At the end of both workshops, each participant presented their sensor objects to the group and demonstrated how they worked. A post-activity survey asked about several aspects of their sensor objects including how they would interact with their object, what they imagined it sensed, and what guided their working process.

Workshops

The first workshop was held at a co-working and makerspace for professional makers, with the majority of the 8 participants recruited through the space membership.

The second workshop was held at Queen Mary University of London, with participants recruited from author CN's professional network. The smaller group (4) allowed a more social experience with continual group discussions and presentations, in which participants engaged more with each other's work rather than only with the facilitators or their neighbours.

The second workshop was divided into two sessions, the first consisting of free exploration (like the first workshop). In the second session (ca. 30 minutes), participants were given the option to make an iteration of their sensor object or work towards a brief to make a sensor for an audio-textile art installation. The purpose of the brief was to provide a focus for their exploration and shift their attention from the visual to the tactile and interactive elements of the sensor material.

Longer exploration

Following the second workshop, the four participants were invited to take a kit home for around 2 weeks. In order to better understand the lines of influence, a sketchbook was included in the kit as data from a sketchbook may be more revealing than an interview (see Rosner's use of 'diary methods' [35]).

They were given an open design brief to re-imagine smart home technology from a tactile or sensory perspective, and to make a proof-of-concept (semi-functional) prototyping using the sensor material. Specifically, they were asked to consider: What if smart technology where made from a sensory perspective? How would you interact with the device? What does that interaction feel like? What does the device do? What is the purpose of the device?

How the designers chose to address the brief was up to them. The outcome could be anything from a pragmatic design solution through to speculative design fiction. The purpose of the brief was to give focus and a starting point to the explorations. After this home exercise, participants returned individually for a debrief interview where they presented their outcomes.

EXPLORATION OUTCOMES

In this section we present the various outcomes from the workshop and long-form exploration.

Workshop outcomes

Table 1 shows a summary of the individual outcomes and interaction gestures. There was no significant preference for one type of conductive and non-conductive material over the others. All the available materials were used by at least one participant. We found that the objects created during the workshop could be classified in two categories based on their interaction modes: *proximity* and *deformation*. Out of 25 objects created during the two workshops, seven were discarded or not working and therefore not classifiable.

Proximity

In these objects the conductive material and magnet are separated by air, and the proximity of the two materials create the interaction. Eleven of the objects had this type of interaction, and three participants created objects solely with this interaction mode. Interaction gestures within this category ranged from holding the magnet and moving it in proximity to the conductive material (*Enclosure*) to more random signals generated from suspending the magnet on a string (*Pendulum*) or holding the magnet to the top of a fringe and waving the object (*Brush* and *Wave*)

Deformation

Deformation covers situations where the magnet and conductive material are part of a single object, separated by a material. Interaction happens through the deformation of the object, for example by applying pressure (*Pressure*, *Squidge*), striking (*Stack*, *Macro ball*), stroking (*Rabbit*) or any other form of interaction that causes the material to deform. Two participants used this methods for both their object and a further four participants made one object with one deformation mode and one proximity, giving the total of nine sensors with the deformation mode.

Hybrids

In the second workshop in particular there was a richness in gesture and interaction style, partly due to the fact that all participants interacted with each other's object. Both of Dana's sensors were interacted with in both modalities. She demonstrated *Rhythm* as a deformation type object. However, when Lauren interacted with the object she did so by moving the magnet in her hand over the object as well as pressing down on the object with the magnet.

Design ideas vs. material

Another theme emerging from the workshop was how participants approached the unfamiliar sensor material in relation to their ideas and concepts of what they wanted to make. In some cases the sensor material would not easily do what the participants wanted to accomplish which gave rise to various strategies for proceeding.

Changing through experience Some participants expected a particular behaviour from their object but found it responded in a different way. This led them to reassess and reinterpret the purpose and workings of the sensor which often led to a more imaginative understanding of how the sensor works. Some participants changed their approach in how they made the following object. Oscar changed from a conceptual way of understanding the sensor to one based on his experience of working with it through the development of his various objects. Carrie stated in her post-activity survey that she went from making something with a potential application to focus on making something that works.

Jamie on the other hand expected his second object, *Pendulum* to have pulsing signals made by the magnet swinging from side to side. He found the result to be "more messy" and "when you touch it the pendulum starts moving and you get sound and it contains the sound for a while after you touched it." Rather than changing the the object itself he changed how he framed the object.

Simplification Several participants found unexpected diversity through simplifying their concepts. Steve for instance could not get his first sensor to work given its complexity and possibly his lack of skills to execute. He decided instead to focus on a single fabric ball and make it in large scale. The result impressed him, that this single object could have such

Sensor	Construction	Interactions
Rhythm by Dana	Strips of cardboard and copper tape of varying lengths with conductive thread and foam connected to the pieces of copper tape.	Tapping, stroking, pushing the magnet underneath; pressing the material with the magnet; plucking conductive thread with the magnet.
Materiality by Dana	Pieces of rubber, foam and velvet stitched onto foam backing using conductive thread with a magnet sandwiched between two pieces of rubber.	Moving the rubber; moving a magnet above sensor; pressing the sensor with magnet underneath.
Brush by Emi	Rubber fringe with conductive tape with a magnet at the top of the sensor.	Tapping; pushing; flicking.
Islands by Laura	Loops of copper ribbon connected to an 'island' of foam and copper fabric.	Moving magnet over the wires while squeezing and tapping the other island with the other hand.
Wave by Ellie	Multiple triangles of rubber, wrapped with wire joined together at one end in a strip.	Waving; tapping; vibrating; touching; stroking.
Pendulum by Jamie	Magnet hanging from a string inside a cardboard housing lined with copper tape.	Tapping the housing.
Enclosure by Oscar	Cardboard enclosure with copper tape on the inside.	Sliding the magnet over the conductive areas.
Rabbit by Rita	Strip of copper tape hidden inside wadding.	Patting; stroking; holding; squeezing.
Stack by Paul	Stack of foam cut in squares with holes pierced at random. Copper wire threaded through the holes, zig-zagging through the layers of foam.	Flicking; crushing; plucking; squishing; hitting.
Macro Ball by Steve	Hand-sized stuffed velvet 'ball' with two magnets inside and a strip of conductive tape on the outside	Squeezing; hitting; throwing the object.

Table 1. A selection of the functioning sensors built during the two workshops

a rich amount of gestures and give immediate feedback. Emi similarly found that simplifying and abstracting her design led to a richer interactive potential. She was interested in exploring the materiality of rubber through her sensors. *Brush*, the first object she made was inspired by a brush as well as the rigid yet flexible rubber material. Her second object *Iteration*, used the core concept of *Brush* copper tape on thin rubber strips, while expanding on the iterative possibilities.

Similar types of objects/interaction, different descriptions

All the participants that used the deformation mode of interaction for their sensor object recognised this similarity when they presented their objects to the group. Yet when they went into more detail about the object, such as its purpose and what it senses, their stories started to diverge. Rita imagined her *Rabbit* almost as a digital emotional support animal, an object that could send a message of distress to a friend when patted. When explaining what the sensor sensed she wrote "it senses my friendship when I pet it – it makes a sound". Paul on the other hand started to make something he thought would sound a bit like a guitar (*Stack*) given the way he had combined the various materials. It did not. In the presentation he explained how he experimented with different placements of the magnet without getting any better results. He described the interaction with the object as hitting it over and over again, which led one of the other participants to suggest his object could be used in a punching bag. Paul concluded that his object "would tell you how hard... how angry you were".

Relationship between sound and material

Several of the participants were interested in exploring the relationship between the sound and the materials. Alice chose her materials for aesthetic reasons, especially the way they looked, but she was also interested in exploring "different densities of sound". Some of the materials she chose were thin while others were thick, and the metal of the conductive materials had different colours which led her to think they might all have different sounds. Dana was similarly interested in "the connotations between sound and material", suggesting that the materials used in her object ought to have different sonic qualities.

Alice's second object also explored the relationship between materials and sound. Alice found that two materials sounded different, leading to a group discussion on whether material properties created a unique sound, whether the affordances of the material led to a different behaviour which in turn created a different sound, or it was simply a perceptual illusion because of the different materials felt different.

Longer-form exploration

During the longer exploration the chosen materials closely aligned with the context where the object would be used (conductive stitching on a placemat or as a bookbinding). This included adapting found objects (cutlery, notebook, postcards).

Two of the participants (Emi and Lauren) prioritised idea generation while the other two (Dana and Alice) refined their

Figure 4. Some of the outcomes from the longer form exlploration. From top left: *Neclace* by Alice, *Interactive books* sample by Lauren, *Posture Help* by Alice, *Meditative home technologies* fur sample by Emi, *Interactive dining* by Dana

outcome through the process. Emi focused on conceptualising in objects, spending her time thinking and sketching ideas of how the sensor could be used in a home environment. She indicated particular interest in the sensor's potential for soft, tangible interaction. Lauren's idea generation took the shape of samples. In the beginning of her sketchbook there are a few ideas of various applications for the technology before ultimately settling on a concept of interactive books.

Dana used her sketchbook not only to capture her own process but also to reflect on other designers' work that she found relevant and inspirational for her own process. There is a sense of refinement in her book going from a complex table setup to focusing on the interactive possibility in the movements between cutlery and plate. Alice's sketchbook shows a similar refinement. She was interested creating a wearable object that could help with the posture of the wearer. The initial sensor *Necklace*, was discarded for being "unwearable" as it was big and chunky. She had not thought of the magnets as she was making it and had some concerns regarding health and safety in relation to magnets and pacemakers. Her second iteration a fabric sample, *Posture helper* shows much more care and consideration as to where the magnets should be placed.

Movement as a common theme

When asked about what their sensor senses the first response from all participants was that it senses "movement". Once they started to explain the sensor in more detail their explanations diverged. Alice described how the movement can "link back to it being like a representation of like, tiredness levels or injuries or something like that." Dana explained how different cutlery produces different sounds and demonstrated the movements the different cutlery. As the movements are different so is the sound. Emi suggested that her furry home device might learn and detect stress and anxiety through daily interactions. The way the user strokes the device will change with stress. Laura imagined her sensor objects sensing movement form the child interacting with the book, possibly with a magnetic wand.

DISCUSSION

In this section we reflect on some of the themes emerging from the design exploration and the two workshops, and what these activities reveal about *following the materials*.

Understanding Imported from Familiar Sensors

Several participants initially sought to understand the sensor material through the lens of familiar electronic sensor components. For example, Steve and Oscar began by wanting to make *buttons*, which was unexpected because the button represents the most discrete possible interactive behaviour while the sensor material potentially enables a rich continuous interaction (a "handle" in Verplank's terminology [41]). Jamie, who had a software development background, initially proposed to make an XY grid of sensor elements, thus importing an idea commonly found in existing digital technology. Oscar, who had an engineering background, went on to produce a series of increasingly conceptual designs (a pressure sensor to put in a mattress or shoes; an abstract object involving spinning magnets). He later reported that he wished the organisers had been more explicit about the continuous nature of the signal.

A particularly interesting case was Carrie (background in textiles, no engineering training) who became increasingly stressed at being unable to conceptualise what the sensor *was*; the inability to fit the sensor into an existing mental model proved an enduring barrier to her engagement with the activity.

Ambiguity

The value of ambiguity in design artefacts is a recurring theme in recent HCI discourse [15, 36, 42]. Gaver observes that "ambiguity is a property of the interpretative relationship between people and artefacts" [15], and in our workshops, the ambiguity emerges not as an intrinsic property of the sensor material but from the participant coming to terms with a sensor which defies easy categorisation. We found three sources of emergent ambiguity: how the sensor works, the meaning of the signal it produces, and the function (or lack thereof) of the objects built with it.

Initially, participants found the sensor ambiguous because it was unknown to them. This ambiguity was felt more strongly for participants with little or no experience of making something with technology (e.g. Carrie). Lack of experience with technology also led to participants drawing erroneous conclusions. Dana reasoned that the length of the stitch she had used caused a louder noise in one part of her sample. This idea stayed with her, so in the later exploration many of her designs had long lines of conductive material. During the debriefing session she asked for confirmation if this was true or not. Alice a had similar (mis)understanding of the technology, saying that the sensor she made during the workshop "senses the length of the thread and different conductive material". Like Dana, her view shifted during the longer exploration at home.

The second type of ambiguity manifested in the meaning the participants gave to the signal and how they described that meaning. Jamie said of his pendulum: "originally I was thinking you could get like a pulse from the signal... that it's just swinging side to side, but then I realised that as you are touching it, it just sort of ... [it's] a bit more messy ... this signal sort of go from when you touch it – it remembers it for like 10-20 seconds." In the third type of ambiguity, the function of the object itself was unclear. This could be seen in Oscar's spinning device, or in Dana's interactive dining experience. Dana imagined many outcomes it could produce, and repeated querying from the organisers yielded several different partially-formulated answers: sometimes sound, sometimes rhythm (of eating), at other times colours.

In other words, the ambiguity of the sensor material, rather than being diminished through the design exercises, was transformed into ambiguous final objects. This may be in part a function of the nature of the semi-functional prototyping exercise, in which the leap from sound output to interactive function remains in the designer's imagination. For such a system to be used to produce fully-functional interactive digital objects, feature extraction techniques (e.g. interactive machine learning) might be deployed.

Co-Creating Objects and Material Understanding

Design processes that Ingold would term *hylomorphic* (imposing a predetermined form on a material) were uncommon in our workshops, where they often resulted in nonfunctional artefacts, and such processes were entirely absent from the longer explorations. However, comparing our observations against previous literature on materiality suggest that there may be several alternatives to the hylomorphic approach. These processes all share the well-established baseline that designers "follow the materials" [19] but differ in the role of conceptual knowledge and the order in which material understanding and specific design outcomes are developed.

Figure 5 proposes three processes which all exhibit a correspondence between designer and material [20]. The Logical approach begins with an exploration of the material aimed at building a conceptual understanding of material properties (similar to Jacobsson's [21] and Karana's [23] description of *tinkering*). Once developed, the understanding is applied to the creation of objects. Process A describes a typical engineering approach, with an emphasis on specifications even if these are gained from practical experience. Material-Driven Design [23] adds important experiential and culturally situated elements to this model, while retaining the temporal sequence that a robust understanding of the material precedes the creation of artefacts using it. In our work, author CN's exploration of the material initially followed a similar process, even though the resulting understanding defied easy verbal explication.

The Conceptual approach begins with a clear concept of the intended final object, and the designer undertakes directed exploration of the material to realise the concept. The understanding of the material emerges through the creation process, and the final object, while embodying the original concept, will have a form that reflects properties of the material. An example is the introductory phase of the *kit-of-no-parts* fabric sensor workshops [32], in which participants learn the materials by creating particular categories of sensor (e.g. tilt, pressure, potentiometer) from example designs: the end point is partly specified with a language of technology while the design process derives from craft practice [14, 33, 44]. We observed this process with some workshop participants, where the material exploration was directed toward a detailed design idea whose instantiation came to reflect properties of the material.

The Intuitive approach begins with an open-ended exploration of material aimed not at characterisation *per se*, but at the creation of objects in an improvisatory and non-goal-directed way. In contrast to the Logical approach, the understanding of the material emerges simultaneously with, or even retroactively from, the objects created, and this understanding may defy easy conceptual categorisation. An example is Vallgårda's *bricolage practice* of interaction design [40], where the bricoleur operates "in-situ and not towards an imagined future." This process was common in our workshops, especially after a determination of infeasibility of the initial concept. Many of the objects created (Table 1) do not have an obvious function, nor (with certain exceptions, such as Oscar) do they emulate familiar types of electronic sensor. Working with the sensor material are in some ways also more similar to working with living materials [13] where the material (interactive) properties changes and shifts depending on how the sensor is put together and given physical form.

Material Improvisation as Grain Indicator

The explorations in this paper, particularly those following the Intuitive approach, could be described as *material improvisation*: co-creating interactive objects and material understanding in the absence of a strong preconceived notion of either. In material improvisation, a theoretical or conceptual understanding of the material is not necessary. In Giaccardi and Karana's *materials experience* framework [16], improvisation privileges the first (*sensory*) level over the second (*interpretivie*) level; as noted above, ambiguity in the understanding of the sensor material can carry through into ambiguous final objects. Alternatively, as seen in the differing descriptions of the material following the longer explorations, the emergent understanding might be contextually dependent, possibly involving *mythical thinking* [40], as in the case of Alice's (erroneous) conclusion that the sensor senses the length of thread.

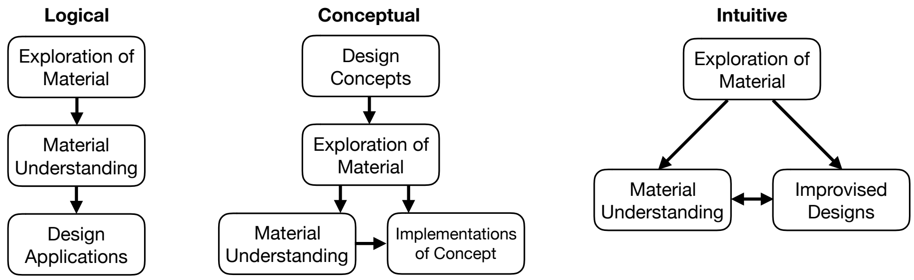

Figure 5. Three processes by which the designer responds to the material. In the Logical approach, understanding emerges through exploration and precedes application. In the Conceptual approach, an exploratory process is directed toward an established conceptual goal. In the Intuitive approach, artefacts and material understanding are co-created in an improvisatory way, with the possibility for understanding to be inferred retrospectively from specific application scenarios.

We propose that material improvisation serves as an indicator of the grain of a material. Ingold [19] does not precisely define *grain*, but he writes of "follow[ing] its course while bending it to their evolving purpose", or "intervening in the fields of force and currents of material." The grain might therefore be characterised as the directions of those forces and currents, defined subjectively according to the influence on the designer. It is not the purpose of this paper to seek a formal definition of Ingold's terminology. Whatever definition is used, it seems evident that grain can be observed only indirectly through patterns of influence on design processes and outcomes.

Material improvisation, through its relative lack of constraints from pre-existing conceptual knowledge or target objects, could be highly sensitive to Ingold's "fields of force and currents". Similar to how iron filings align themselves with a magnetic field to reveal otherwise unseen lines of force, how designers improvise with material can provide an external manifestation of the latent patterns of influence that we could say in some manner constitutes the grain of the material.

The Role of Sound

What, then, might be the grain of *this* specific sensor material? Even our use of the term "sensor material" raises questions, in that the sensor technology applies to a wide range of conductive and non-conductive substrates, whose choice will surely influence the design process, to the point that we might instead speak of a class of materials or a proto-material. However, what is consistent across every variation is the dependence on invisible electromagnetic force, and hence the requirement for a secondary, dependent medium to manifest those forces. We have deliberately chosen sound.

Audio plays a significant role in physical interfaces [43], but as we did not know the form or interaction of the objects that would be built by the workshop participants, we could not shape the audio to reflect the physical characteristics of the object. Instead we kept to a simplistic sound and mapping that would not interfere nor lead the design, but would only expose the underlying electro-magnetic relationships.

Sonification allows for a more nuanced recognition of patterns within data than visual or haptic displays [7]. It is likely that the audible patterns discovered in Dana's Interactive Dining project caused by picking up and gesturing with different utensils would not have been noticeable in another modality. The sound is a characteristic of the composite material, not of any singular material within that composite. If a modality besides sound were used, there is a question of whether the composite would be transformed. The sound is separate from the composite of tangible materials and therefore not an essential part of the composite. The sound itself is malleable in that another sound or another mapping between the sensor and the sound synthesis could have been used. The sound could even be replaced with another modality such as haptic vibrations or pulsating light. It is clear that a subset of the workshop participants viewed the composite as separable in this way. However, others may have viewed the sound as an intrinsic property of the composite itself.

CONCLUSION

We have created a new type of sensor material (or perhaps a proto-material) from which a wide diversity of interactive objects can be crafted, but whose operation defies easy conceptual categorisation. In her design exploration, author CN focused considerable time asking what the signal from the sensor *means*, never reaching a complete answer despite investigating theories from digital signal processing and electromagnetism.

But in a way, finding a clear meaning and resolving ambiguity is not required. Dahlberg et al. write: "When we let the things themselves present themselves in all their multiplicity we let them show all their possibilities, all their horizons, presentations as well as appresentations. It means that we do not impose ourselves upon the things, that we do not force them into linguistic categories, that we do not make definite what is indefinite" [11, p. 122]. If there has been one thread woven throughout this paper, it has been an embrace of the indefinite, not as justification for arbitrary decisions or unapproachable technologies, but as a source of richness. Indefinite or ambiguous materials can still exhibit a grain which can be discovered through the development of tacit knowledge and craft practice.

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