The To-and-Fro of Sense Making: Supporting Users' Active Indexing in Museums

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Based on case studies from a heritage/museum context, I present and illustrate the notion of "spatio-contextual embedding," which conceptualizes installation designs that augment real objects and environments while keeping these primary focuses of attention. Key for this "embeddedness" is that interaction is contextualized within a meaningful setting, creating relationships between system and environment. While retaining a focus on original objects or environments, it supports user's active engagement and sense making by inviting, enticing, or forcing them to draw connections. At the heart of this is "indexing": mindful acts of referencing back-and-forth between here and there, connecting objects or representations. Analysis of case studies provides a repertoire of examples of "indexing," and examples for high- and low-tech installation designs that foster drawing of connections.

Two core values for design underpin the argument: (1) primacy of real objects and environments and (2) supporting human agency. The case examples highlight how technological arrangements may support or hinder indexing activity. This is condensed into potential design strategies. This article contributes to design knowledge on design for human agency, sense making, and mindful engagement with our environment. "Indexing" is relevant beyond the heritage setting domain, as part of HCI design in support of human agency.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**; **Empirical studies in interaction design**; *Ubiquitous computing*

Additional Key Words and Phrases: Embedded interactions, embodiment, situated interaction, indexing, museum installations, interaction design strategy, augmented environments, engaging user experience

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1. INTRODUCTION

Our small group is standing on the outlook of a castle ruin on a hilltop, facing the magnificent scenery of the wide lush-green lowland of the Allgäu before us, which at the horizon is interrupted by a steep mountain range. We can see the village that we passed on the way up and a town in the far distance. A panel attached to the balustrade shows a simplified depiction of the view, employing the usual scheme of text floating in the sky, with arrows pointing from the text to the various points in the scenery. One of us points out a famous mountain on the panel, and then, points into the distance, saying its name, while the rest of us attempt to follow his reference. The panel assists

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us in finding and identifying some of the mountains further out, which in the haze are hard to see. We remember that Neuschwanstein must be somewhere right across us, and use the panel to figure out where it is, pointing out into the distance and moving the hand while searching, repeatedly glancing back-and-forth between the panel and the mountain range where the castle is barely visible against the dark mountains as a tiny white dot. We enjoy our shared activity of sense making and engaging with our surroundings, aided by this simple panel. What we are doing is a simple example of what I will refer to in this article as *indexing,* that is, the mindful referencing back-and-forth between two representations or entities, relating them to each other and creating new meaning while doing so.

Most digital technologies tend to break up this oscillation by either pushing a digital representation to the foreground of attention or by merging representations, for example, with augmented reality views that directly overlay annotations and labels over a real view. What often is lost in this process is the users' active and purposeful discovery and creation of connections and references (which may go in both directions). In this article, I will investigate how technology can explicitly support and foster this human activity of "indexing."

In particular, technology designs that are *spatially contextualized and physically embedded* seem to engender and support such indexing actions and can thereby increase our engagement with our surroundings. But this requires careful design—it does not come automatically just from juxtaposing a real-world object (or scenery) with related digital content (or an old-fashioned text panel, as in the introductory story).

With the proliferation of technology into museums, this has become a salient issue for this domain. It is common to see information terminals and large touch-sensitive tables offering copious amounts of background information or providing access to simulations and educational games related to the exhibition contents, not mentioning the ubiquitous audio guides. Yet it is questionable whether visitors actually want to read large amounts of text on site (cp., [Hornecker and Stifter 2006] and [Adams et al. 2004]). There is also concern about visitors being distracted from the actual artefacts on display [Bannon et al. 2005; Macleoad 2013; Martin 2000; Pujol-Tost 2011; Schwarzer 2001; vom Lehn and Heath 2003] as well as a gradual rediscovery of the role of the material object and multi-sensorial, embodied experience [Dudley 2010; Bedford 2014]. Museums that have original objects on display, will typically value interactive installations as successful if these increase visitors' appreciation of and focus on these objects [Adams et al. 2004]. Moreover, museum research indicates that visitors are more likely to understand the meaning of objects when it is displayed in context [Perry 2012]. Thus, spatio-contextual embedding is a particularly well-suited design strategy for technology design in the heritage sector.

1.1. Introducing "Indexing" and "Embedded Interaction"

The analysis presented here is based on a series of case studies from a museum/cultural heritage context. In the case study reported first [Hornecker 2010a], human practices of what will be referred to as indexing were uncovered—acts of referring back-and-forth between the here and the there, drawing connections between different entities or representations, as in our little introductory story. We further realized that these indexing acts occurred in interactions around installations that can be classified as being embedded in their environment.[1]

[1]Our awareness of the utility of content crafted to intrinsically connect to location had been raised in a prior project [Halloran et al. 2006], but this had not yet been clearly identified. We had realized the importance of carefully crafting mobile content so as to direct the listener's / reader's attention toward the environment,

The understanding of indexing suggested in this article has its base in a linguistic understanding of indexical expression in communication [Bar-Hillel 1954] and of deixis as a non-verbal means of indexing [McNeill 2000, 2005] and will be illustrated via examples, grounded in data. Indexical expression and deixis are ubiquitous in our lives and an elementary part of our communication and coordination practices, as shown by conversation and ethnographic studies. This linguistic-communicative understanding is extended to include the notion of "indexing for yourself," inspired by ideas from Distributed Cognition [Hutchins 1995; Kirsh 1995a, 1995b, 2010], which highlight how, for example, pointing can serve as a memory aid for individual cognition, using the external environment as a resource to aid cognition.

In using and combining these two understandings, I do not define indexing in a novel way, although the term is used in a specialized way to refer to the back-and-forth between entities at different locations (and not just simple pointing at *one* distant object). The contribution of this article lies in investigating what makes out systems that support this type of indexing as a complex form of sense making and reciprocal relating between different representations/entities and as a human activity through the analysis of case studies and examples. This analysis is inspired by perspectives on "indexing" practices from Ethnography and Distributed Cognition. While ethnographic research and communication studies tend to focus on describing indexing actions and how they relate to the environment, the focus here is on how indexing actions are engendered and triggered.

This endeavour builds on prior work that has emphasized that interactivity is a property of users, not of systems [Heath and vom Lehn 2002], and argued for the need to support user agency or "proactive people" (rather than proactive computing) [Rogers 2006]. It stands in a tradition that aims to support people's sense making [Suchman 2007] or meaning-making [Dourish 2001] and has an action-centric focus, focusing on interaction in context and on systems as providing resources for (social) action (cf., [Fernaeus et al. 2008]). Indexing, as described in this article, is a way of users actively (and mindfully) engaging with their environment. In leaving the indexing to the user (only providing an invitation to do so), the design leaves space for the user to explore and wonder [Jones 2011]. This requires interaction techniques "that put us back in touch with our surroundings" [Jones 2011]. Another example of such techniques is "head-up games" (cf., [Soute et al. 2010]), which make minimal use of the screen in order to allow for social interaction and physical engagement. This is also a concern for museums that recognize the role of group interactions and sensorial as well as imaginative engagement for visitor experience and learning [Bedford 2014; Dudley 2010; Perry 2012].

Luff et al. [2013] have recently argued that the focus on embodied interaction has taken attention away from how activity is embedded within an environment and local ecology. This may be more a question of emphasis, as these are not contradictions. Suchman [2007] emphasized in her work on situated action that human action is fundamentally concrete and embodied, situated and social. Phenomenologist philosopher Merleau-Ponty [1962] stated that we, by having bodies, are necessarily situated in the world, and thus, always engaged with and directed towards it. The physicalities of objects, our bodies and our environment intersect in interaction [Hornecker 2011]. This introduces the second core idea underlying this article and highlights how tangible systems are physically embedded in real space, and thus, situated in social and physical contexts [Dourish 2001].

Here, *embedded interaction* is understood in a different sense to the technical view of embedded computing, and refers to interaction with systems that are physically

with content that needed to be encountered in-situ as it would only achieve its full meaning from being embedded in a specific location. We will return to this in the background section.

embedded, contextualized, and integrated into a meaningful spatial setting. Interaction is embedded in this context. Spatial contextualization means that the interface cannot be fully interpreted without reference to its setting. Interactions thus tend to index into these surroundings and take place around the interface while referring to it. The case studies will provide a series of examples for *spatio-contextual embedding* to illustrate this concept. Such embeddedness allows for "indexing activities"—the drawing of connections between system content and the environment (or between parts of the latter), engendered by how the system is integrated and embedded into the environment. This is because indexing is an embodied relationship with a situation or context. This argument about the relation of embedded interaction and indexing can be extended to mobile applications and mobile content that intrinsically relate to location and cannot be understood removed of this context, i.e., [Halloran et al. 2006], but the current article will focus on non-mobile museum installations.

From a design standpoint, the provision of indexes is often considered a quality of an interface. The design focus then is on the provision of indexes by the system. But from an ethnographic viewpoint, it is people who do the indexing, looking back-and-forth, making connections by pointing or verbally referring to objects, and their overt behaviour makes this activity visible to the observer. This is analogue to the two alternative understandings of "awareness" within CSCW. While authors that focus on interface design tend to describe awareness as a feature of the interface (which provides awareness information (cf., [Gutwin and Greenberg 2002]), in the works of Heath and Luff [Heath et al. 2002b] and Schmidt [2002], awareness is described as an interactional accomplishment of human actors. This leads to the question of how technological arrangements may hinder or support this accomplishment. In a similar vein, our interest is in understanding what features of a technology engender and support the human activity (or behaviour) of indexing.

The kind of back-and-forth indexing that this article explores is a resource we draw upon when we communicate with each other and engage with the world around us. Our emphasis here is on the active production of indexing by people. Too often, technology aims to direct and steer us, giving us directions. An alternative, in the tradition of technology that supports human agency [Rogers 2006] is to design technology systems in a way that supports the human activity of indexing which contributes to sense making and mindful engagement with our environment.

This article has *three contributions*:

(1) it illustrates the role of this referential back-and-forth indexing in human sense-making activities with data from one larger case study and further examples;
(2) these demonstrate how technological systems can support or hinder indexing by their spatio-contextually embedded design; and
(3) based on this analysis, the article suggests eight design strategies or "sensibilities" [Ciolfi 2004; Fitzpatrick 2003] for the design of systems that support indexing.

After a background review, the main case study (Section 3) introduces and illustrates the conceptual notion of *indexing* and of *spatio-contextual embedding*. The author conducted an analysis of several installations in a museum, of which one was very decontextualised, resulting in many interactions but little actual engagement with the contents [Hornecker 2008], and another was contextualized and spatially embedded, resulting in observation of multiple instances of *indexing* behaviours [Hornecker 2010a]. This was initially discussed within the context of tangible interaction. Additional examples of museum installations provide further evidence of indexing activity, illustrate *embedded* designs, and highlight issues to be taken into account when designing for spatial embedding, illustrating design decisions that may negatively affect users' ability to index easily and fluidly.

The article then introduces a number of design strategies that have emerged from the analysis of these installations. Examples of problematic designs have been particularly useful as a contrast for highlighting design considerations that remained implicit in successful cases. The closing discussion relates the notions of spatio-contextual embeddedness and the design strategies to other work in HCI research and delineates issues for future research.

2. BACKGROUND

The following sections provide an overview of the different uses of the notion of indexing within HCI and related disciplines. This will help to clarify what is meant with *indexing* (rather than the notion of an index). We start with related work in HCI and related areas, including work on gesture and indexing from gesture studies, ethnography, and distributed cognition, which informs our understanding of indexing and analysis of case study data. Furthermore, research on museum installation design and visitor research is discussed, focusing on work emphasising how to augment exhibit artefacts in a way that does not divert visitor attention away from the artefacts and supports social interactions.

2.1. The Notion of Indexing in HCI and Related Disciplines

The notion of an index is well known from book indices. According to the Oxford dictionary (http://oxforddictionaries.com/definition/english/index), the word as a noun refers either to a book index, to "a sign or measure of something," a mathematical index sign, and as a verb, to recording something in an index. Its linguistic origins are important for the tradition relevant for this article—it derives from the Latin "index" for forefinger, informer, sign, coming to also mean "pointing," and also refers to the entity pointing to a fact (being an index for something). Deixis (gestural pointing) thus is a form of indexing.

A strong tradition within HCI for the notion of indexing is semiotics, where icon, index, and symbol refer to different types of signs [Peirce 1931–1958]. Indexical signs *indicate* something, e.g., smoke indicates fire, with a non-arbitrary, causal connection between the sign and the object referred to. Semiotic analysis and semiotics-informed design of user interfaces has thus become a field of its own [de Souza 2005]. Instead, our understanding is closer to the tradition of gesture studies, ethnography and ethnomethodological analysis, which focus on the ways people coordinate their actions [Heath and Luff 2000], in particular, through bodily behaviours. What makes these relevant here is the focus on users' indexing actions and in-detail investigation of the semiotic resources of talk, bodies, and environment that participants in a situation draw upon [Goodwin 2000]. The discussion is informed by the field of gesture studies [McNeill 2000] and the notion of indexing is strongly inspired by ethnographic workplace studies focusing on (social) coordination practices [Heath and Luff' 2000] that highlight the role of gesture for coordination and shared action, and by distributed cognition and embodied cognition that highlight the role of the body and the environment for cognition [Capuccio et al. 2013; Hutchins 1995].[2]

2.1.1. Indexicality as Provision of Indices. In HCI, we often find the notion that indexes are a property of the artefact (or representation), encouraged by the semiotic tradition (although semiotics also emphasizes the process of interpretation) and dictionary definitions of indexical signs, rather than the idea that people actively index to make connections between different things, which is our focus here. Kjeldskov and Paay

[2]not to be confused though with what Garfinkel refers to as Indexicality as a radical understanding of the context of social action.

[2006] utilized the notion of indexicality in HCI in context-aware systems. By locating information in time and space, temporal and spatial indices can be employed, reducing complexity and the amount of symbolic and iconic representation. This means, for example, only providing information on users' mobile devices that is relevant at the current time and location, and tailoring it to refer to the current context (physical or social, such as choice of restaurants depending on group constellation). Walking directions may be given in relative terms, explicitly relating to the current location. Information can also be indexed into an environment by placing it on augmented photographs, so the user can match up photo and environment. Paay et al. [2008] found that users found it easier to understand and use information contextualized to location than to social situation. They utilize this approach for the design of a location-based storytelling game, building on the idea of augmented photographs. Users have to line up the augmented photographs and the physical location in order to recreate their indexical relations. The emphasis in these analyses still tends to be on providing and suggesting indexes, and less on human practices of indexing that are engendered by the system. In contrast, the focus for the current article is on investigating and supporting users' *active* indexing practices.

2.1.2. Indexing in Gesture: Deixis in Linguistics and Communication Studies. Another tradition that focuses on human practices of indexing is related to communication studies and the investigation of the structure of human conduct in ethnomethodology and conversation analysis. In linguistics and language philosophy, an indexical behaviour or utterance points to (or indicates) something else. The meaning of an indexical statement depends upon the context it is embedded in [Bar-Hillel 1954; Garfinkel 1967] speaker, location, or time ("me, here, now"), fulfilling a similar function as deixis. Indexical expressions assume common ground in the current situation, which enables the recipient to decode the reference, and saves the sender from explicating everything.

Deixis is considered the "primeval indexal sign" since "deictic or pointing gestures (...) are not representational but instead act as Peircean indices picking out their reference by virtue of a shared spatio-temporal proximity with them" [Haviland 2000]. Deictic gestures can locate real, imagined, or conceptual entities in space from a reference point [Haviland 2000; McNeill 2005]. The external environment and situation history situate deixis, which can exploit features of location and past communication.

In HCI and Computing, gestural systems have been based on the linguistic schema of cooccurring speech and gestural deixis, enabling the user to employ linguistic shortcuts to simplify expression. The earliest example is Bolt's [1980] "Put that there" system, which allowed users to specify actions verbally and explicate objects and locations to act on by pointing. Similarly, newer gestural interaction systems, including touch screens, rely on simple deictic movements and gestures.

A rich tradition investigates the linguistic and cognitive function of gesture, and increasingly defines gesture and language as an integrated system [Kendon 2004; LeBaron et al. 2002; McNeill 2000, 2005]. In micro-analysis of human interaction (in ethnomethodology, interaction analysis, and in modern gesture and language studies), it has become common to treat gesture and speech as equal acts, where a gesture may constitute a complete utterance, or speech and body behaviour form a mutual performance [Jones and LeBaron 2002]. This is often expanded to include the material environment and social context. Hutchins and Palen [1993] describe space, gesture, and speech as being used to construct "complex multi-layered representations," where the spatial organization of artefacts and the positioning of gesture provide meaning. Pointing is a prime example, as it relies on the visibility of the referent. Goodwin [2000] interprets body movement, gesture, talk, and mutual orientation as sign systems that interactors deploy as semiotic resources, which mutually elaborate each other. Gesture is one

of several simultaneous semiotic fields that participants in a situation can draw upon, including the social, cultural, material, and sequential structure of the environment.

Most work in communication studies and linguistics emphasizes the communicative function of gesture and deixis for establishing shared attention [Clark 2003]. In deictic gesture, hand shape may vary, and any movable body part can point, even the chin or lips [Clark 2003; Haviland 2000; Kendon 1996]. Moreover, deictic and other gesture types are not distinct categories, but multifaceted, having iconic and deictic as well as metaphoric components: Pointing "can trace a shape of what is being pointed at" [Goodwin 2003] (cf., [McNeill 2005]).

The understanding of indexing laid out in this article has its base in a linguistic understanding of indexical expression (and deixis as a non-verbal means of indexing), where gesture and language are "co-occurring and interrelated phenomena" [Jones and LeBaron 2002]. It goes a step further than simple pointing to an external referent, beyond "this" and "there." Our work focuses on how some indexing actions serve to draw complex connections between "here" and "there," between "this" and "that." Goodwin [2003] provides an example of this kind of back-and-forth indexing, where an archaeologist points out a place on a site map and the corresponding spot on the ground, requiring the other person to repeatedly shift gaze. This is a complex accomplishment on both sides, who have to shift attention to see where the other looks and whether they see the other's gaze, in order to establish whether they achieve shared understanding and attention. In lieu of a better phrase, the word "indexical" is used in the current article to refer to the reference from here to there, highlighting a relation, rather than just the deixis of "this, there" right in front of me.

2.1.3. An Ethnographic Perspective. Indexical behaviour has also played a big role in the analysis of ethnographic work studies, which have shown how co-workers make use of the shared environment in coordinating action and collaborating [Heath and Luff 2000]. This tradition is heavily influenced by communication analysis and ethnomethodology. Ethnomethodologically informed workplace studies highlight "the interweaving of talk, visual conduct, and features of the material environment" [Luff et al. 2013] as a resource to support communication and collaboration. These studies reveal the work invested by collaborators to make their actions visible and legible to others, as a part of embodied and situated action. Beyond the study of bodily behaviour, the ethnographic perspective highlights that it is people who do the indexing, looking back-and-forth, making connections, as an interactional achievement.

This approach has been utilized in a range of areas from the analysis of distance communication, coordination work in control centres in the London underground or air traffic control, to studies of robot guides in museums. Studies of video conferencing systems reveal how fragmented views with separate windows for "talking heads" and the workspace disrupt people's ability to unambiguously refer to and point at objects [Heath and Luff 2000, chapter 7; Luff et al. 2013]. Not only is it difficult for the recipient to perceive and interpret gesture, but it also is difficult for the sender to adapt and tailor their gesture for the recipient. Hindmarsh and Heath [2000] emphasize the importance of "recipient design" for visual conduct, taking into account addressee orientation and situation (cf., [Gooodwin 2003]), and illustrate how the entire body (including gaze and body orientation) is used to direct attention to the referent object. This includes, for example, moving one's own body out of the way to ensure the other can see a pointing gesture, and delaying gesture or verbal referent until the addressee can spot the object referred to.

Specifically of interest for this article is the work by Heath, Luff, vom Lehn, and colleagues in the area of museum visitor studies, which reveals the social aspects of visitor experience and behaviour. In museum conversations between visitors, Heath and vom

Lehn [2004] found similar roles of gesturing as previously observed in work studies, where visitors used body posture and movement to discriminate objects, negotiate what to look at and how to look at it. These studies also illustrate recipient design, enhanced by a sense of drama when participants aim to entertain their company. Gesture and pointing play a prominent role. The workplace study tradition has inspired research in other areas where indexical or meta-pragmatic aspects of behaviour play a role, such as performance [Reeves et al. 2005]. Performers very explicitly and expertly design their actions to be read by the audience, exaggerating, or performing extraneous movements. Human-robot interaction also benefits from a clearer understanding of human implicit communication and coordination mechanisms, which robots may emulate [Yamazaki et al. 2009].

Ethnomethodological and conversation analysis studies are primarily concerned with how participants coordinate their actions, and what resources they draw upon, and do not consider cognition and learning. We thus turn to distributed cognition studies, which also conduct micro-analysis and focus primarily on the cognitive role of the interactions observed.

2.1.4. A Distributed and Embodied Cognition Perspective. While communication studies and psycholinguistics tend to focus primarily on the communicative and disambiguating function of gesture, distributed cognition highlights its cognitive function. Gesture often has a double function: "a good deal of our behaviour has communicative function without communicative intent" [Hutchins 1995, p. 233]. It is well known that gestures are also used when nobody can see us. McNeill [2005] describes gesture, language, and thought as different sides of a single mental process, and argues that language is not just a static product, but a dynamic process, which drives and develops thought. Gesture in similar ways supports and develops thought, as shown by Goldin-Meadow (cf., [Goldin-Meadow et al. 2009]). "Instrumental gesture" facilitates or enhances thinking processes [Cappuccio et al. 2013] by displaying and materializing parts of thought, thereby making it available as an external representation that can be perceived and reflected upon. We can thus interpret gesture as a temporary annotation of the environment [cf., Kirsh 2010]. This is not new—Hutchins [1995] described the transient representational effect of drawing lines with a finger on a navigation chart: "The memory of the trajectory of the fingers decays with time, but it seems to endure long enough that several of these can be superimposed on one another and on the perceptual experience of the chart." This transient, fleeting nature of gesture as a representation might constitute a useful quality, since it erases itself, allowing for multiple overlays. Gesture leaves the object of attention intact, while highlighting and animating aspects of interest and guiding attention [Heath and vom Lehn 2004]. The fact that gestures unfold temporally [Goodwin 2003; McNeill 2005] enables them to be aligned with speech and actions, and with the actions of others.

Moreover, gesture "for the self" (which Streeck [2009] refers to as "conceptual gesturing") can organize cognitive action kinaesthetically and visually in a form of embodied cognition. Steier [2014] describes how visitors to an arts gallery mimic the posture of paintings in an interpretative process of bodily internalisation (where mimicking a pose evokes an understanding of the pose's emotional meaning), which then attains communicative function for the visitor's companions.

Theories of external representation [Scaife and Rogers 1996] and of distributed cognition [Hollan et al. 2000; Kirsh 1995b] share an emphasis on the mind as enhanced and augmented by outside representations. Both theories focus on the ways in which we exploit the properties of objects and manipulate them to enhance cognition. Kirsh [Kirsh 1995a; Kirsh and Maglio 1996] investigated the role of epistemic actions such as changing the arrangement of objects, occluding and pointing at them, which, while not

necessary to solve the task, reduce cognitive load. Epistemic actions create constraints, hide affordances, or highlight elements that serve as future invitations or triggers for action, thus creating an index for future action.

Similar to other gesture, pointing can be "part of private cognitive processes and an element of communication," as observed by Hutchins [1995]. People point and gesture towards objects as a strategy of distributed or external cognition [Hollan et al. 2000; Hutchins 1995; Kirsh 1995a, 2010; Scaife and Rogers 1996]. Here, pointing may serve as a reminder, mark out something visually in space, or be part of a conversation-with-oneself. Bodily deixis can be interpreted as an element of embodied cognition, marking out different elements that are to be compared or counted, occluding them, supporting the management of attention (cp., [Kirsh 1995a]), and often mirroring mental activity in physical action. At the same time, these bodily actions can be read by others and attain communicative function.

Theories of embodied cognition also support the view that gesture has a cognitive function [Alibali et al. 2014] and the theory of the situated and extended mind emphasizes the role of body and environment [Clark 1997]. Cappuccio et al. [2013] discuss the cognitive function of pointing as instrumental gesture. In pointing, "the pointing subject himself can look into the direction indicated by his own pointing finger" and can shift attention between the indicated direction and their own index finger "that symbolizes attention towards the very same direction." Pointing thus externalizes the possibility of gazing into a certain direction and symbolically represents the pointers' direction of gaze, making it available to the agent. This supports the agent in controlling their attention and supports them in shifting attention quickly.

Unfortunately, while the Distributed Cognition perspective is conceptually useful, analysis of individual sense-making from observational material is difficult (unless the utilized strategies and their outcomes are clearly visible) as internal cognitive processes tend to remain invisible. Nevertheless, asking what purpose an action might have from a Distributed Cognition perspective expands our analytical insight.

For example, in social situations, it may be indistinguishable for an observer whether pointing is primarily performed as a "service" for others, or for oneself. Actions such as a simple gesture might serve multiple purposes [Kendon 2004], or appropriate a different function in retrospect, when observers interpret and respond to it [cf., Hutchins 1995]. The meaning of an utterance or action is a shared, and often incomplete, emergent and *post hoc* construction of the people involved. Thus, while ethnographic studies rarely emphasize the cognitive role of deictic actions, a distributed cognition perspective may complement the ethnographic stance. For our discussing of indexing behaviours, both perspectives are relevant.

2.1.5. Designing for Human Indexicality in HCI. A new issue for HCI emerging from the studies presented in the main part of this article is how to design for indexicality. Different from the predominant use of indexing in HCI, this does not refer to the provision of indexes, but leaves it to users to do the actual indexing, assigning agency to them (Rogers [2006] suggests designing for pro-active people). This entails purposely enabling users to make comparisons and references in both directions. Bidwell and Browning [2010] take a related approach that focuses on how indexicality adds coherence and meaning to social action, and how people make use of features of the environment as mnemonics and glance at these, referring to them, omitting verbal references. In this situated action, the environment provides an implicit context for conversation and social interaction, supporting shared understanding. Rantanen [2010] analyses verbal descriptions of clues in geocaching and points out how these rely on indexicality to provide levels of meaning beyond literal meaning, a situated meaning that can only be interpreted in-context.

In one of the author's previous projects, the team realized the importance of carefully crafting mobile content so as to direct the audience's attention towards the environment. In the Chawton House project [Halloran et al. 2006; Weal et al. 2006], a mobile, context-aware system was developed in collaboration with curators and teachers. This resulted in a technology-enhanced fieldtrip for children to a historic estate, and in concepts for guided tours. The project's focus on enhancing the existing locale is related to what in this article is termed "spatio-contextual embedding." The fieldtrip had pupils engage with the historic estate's extensive gardens to gather data and ideas for a piece of creative writing, using the setting for exploration and inspiration. The mobile experience utilized mobile content and prompts to direct attention towards the environment and make pupils engage with it. This is related to so-called "head-up interaction" [Soute et al. 2010], making minimal use of the screen to allow for social interaction and physical engagement. In a similar vein, Jones [2011] asks to find interaction techniques "that put us back in touch with our surroundings" and "help us drift or float around an area." The type of mobile experience developed was intrinsically connected with the location. The researchers wanted to replicate the kind of story telling that curators engage in when giving tours, that is, telling stories about objects and locations that are somewhere else, but in sight. The strategy chosen was to use short information snippets and instructions that direct toward the surrounding landscape, making users search and discover (cf., [Bidwell and Browning 2010]), instead of presenting information that just relates to the "here and now." Thus, content and prompts often asked to go out, imagine, search, and draw relations. Relations could be spatial or historical, imagining how somebody from another century and social background would experience the current location. Location was primary for this activity, and many instructions only achieved their full value from interaction with the environment, for example, to "search someplace spooky," or to "record anything you might hear, see, smell." Beyond noticing and reflecting (cf., [Schaefer et al. 2010]), the design philosophy promoted wonderment, imagination, and independent discovery [Bidwell and Browning 2010; O'Hara and Kindberg 2007]. The system prompts thus triggered activities with indexical character. Not only were the instructions indexical by being given in specific locations (as in Paay et al. [2008]), but they also asked to draw connections, or to react in imaginative ways.

2.2. Museum and Visitor Studies: Hands-on or Minds-On Interaction and the Role of Objects

We now return to the application area that this article focuses on. Over the past decade, there has been increased interest in the field of visitor studies and museum research in the details of visitor behaviour in museums (beyond measurements of "dwell time" or attraction), and the multi-faceted intellectual, emotional, and social experience that unfolds in these settings [Bedford 2014; Bitgood 2013; Doering 1999; Heath and vom Lehn 2004; Humphrey et al. 2005; Perry 2012]. The role of social interactions between visitors (e.g., families) for the museum experience [Falk and Dierking 2000; Falk and Dierking 2012; Kelly et al. 2004; Perry 2012; Sanford et al. 2007; vom Lehn et al. 2007] and for museum learning [Ellenbogen et al. 2004; Gutwill and Allen 2010; Heath et al. 2005] is generally acknowledged. Many publications within visitor studies and HCI emphasize that the traditional dominant model of interaction for museum installations only supports the dialogue of a single user with the system, undermining the ability of others to participate [Heath et al. 2005] and highlight the importance of supporting visitor groups [Ciolfi 2013; Ciolfi and Bannon 2002; Hornecker and Stifter 2006; Kelly 2002; vom Lehn et al. 2007].

For interactive installations to be successful, a core characteristic is what Allen [2004] refers to as immediate apprehendability (visitors need to quickly grasp how to interact) and Bitgood [2013] operationalises in the Attention-Value model as the

result of (1) the ease of detection and (2) recognition of the "relative value" of spending attention. While well-designed digital installations can increase the time spent with an exhibition and with individual exhibits [Gammon and Burch 2008; Economou 2010], the "absorbing power" of screen displays can overshadow the surrounding artefacts, and design of installations is especially demanding when these are intended to make visitors simultaneously relate to physical exhibits [Economou 2010].

Some museum researchers and practitioners are sceptical of the role of interactive installations [Allen 2004; Bradburne 2002; Whitcomb 2006]. A radical argument states that interactivity is a property of users, not of systems, pointing out that many interactive installations impoverish social interaction and limit co-participation [Bradburne 2002; Heath and vom Lehn 2002; Heath et al. 2005]. In particular, it is not necessarily the installations with the most interactivity (or content) that make good and engaging exhibits [Allen 2004; Heath and vom Lehn 2002; Hornecker and Stifter 2006]. Museum educators further emphasize the need to go beyond "button pushing" [Allen 2004], and instead to support discovery, sense/meaning-making and imagination (cf. [Bedford 2014; Ciolfi and Bannon 2002; Diamantopoulou et al. 2013; Humphrey et al. 2005; Perry 2012]). Hands-on interaction should result in "minds-on" engagement, and active engagement does not necessarily require manual interaction. This focus on sense-making or meaning-making is related to current models of museum learning as dialogic, constructivist and contextual [Falk and Dierking 2000; cf. Perry 2012] where visitors construct meaning in a free-choice learning context.

Curators interviewed about their practices of developing interactive installations stressed the importance of materiality in experiencing heritage [Maye et al. 2014]. For museums that have authentic objects in the centre of experience, the question is how to augment exhibits so that visitors focus their attention on these objects, increasing understanding and appreciation [Adams et al. 2004; Ciolfi and Bannon 2002; Economou 2010; Kelly et al. 2004; Macleod 2013] and how to encourage them to make connections [vom Lehn et al. 2007]. Furthermore, if an interactive experience is set in an evocative and rich setting that is meaningful in its own right (and not in a standard gallery case), the design should be place-sensitive and integrate into the setting [Ciolfi and McLoughlin 2011].

Museum professionals usually regard the enhancement of object understanding as the primary aim of any technology [Adams et al. 2004; Pujol-Tost 2011], creating a conflict between exhibit objects and technology. Screen-based technologies have been found to work as "attention-grabbers" at a risk of detracting from the original artefacts on display [Martin 2000; Pujol-Tost 2011; Schwarzer 2001; vom Lehn and Heath 2003]; mobile devices and large screens suffer similar issues. Heath and vom Lehn [2002] found that some visitors may watch a video and engage with an interactive instead of looking at the object, especially when galleries are crowded. Pujol-Tost [2011] argues that ICT applications in museums often have a weak spatial and conceptual relationship to objects and are not well integrated into the exhibition flow. She calls for more work on *integrating* ICT applications into exhibitions so that these intertwine with physical elements and the space (instead of self-*contained,* and thus, spatially and conceptually isolated ICT applications, or *discrete* systems that relate to exhibits but remain separate). This benefits not just understanding of real artefacts, but also of digital interactive content, since visitors are more likely to understand the relevance of artefacts or objects that are placed in context [Perry 2012]. Our concept of *spatio-contextual embeddedness* is a continuation of this type of integrated systems.

Information screens and computer games are less popular with visitors than often assumed. This was found in one of our own studies [Hornecker and Stifter 2006] where visitors explained they would rather explore the museum than read long text pages, and wanted to experience things they cannot elsewhere. Adams et al. [2004]

discuss similar outcomes from visitor interviews in a Natural History Museum, which ranked computer-based interactives at lowest preference in a list of exhibit formats. That is, visitors want the unique and special in the experience. Finally, resonance and experience of wonder [Bedford 2014] can have emotional impact. Falk and Dierking refer to "reverential experience" [Falk and Dierking 2012]. Dudley [2010] argues for the importance of physical, multisensory experiences with material things—even if these experiences might be imagined—that produce emotional and personal responses. Moreover, some visitors are especially attracted to and excited by authentic objects, their aesthetics and making, or by physical sensations and experiences [Pekarik et al. 2014]. Bedford [2014] describes "somatic understanding" as pre-linguistic, physical experiences that provide us with insight through mimesis, empathy, or physical action. She points out the role of situated and embodied aspects of imagination and experience and the role of objects (their realness and narrative power). For example, standing in front of the giant dinosaur skeletons in the first case study of this article and walking around them could be described as a somatic and embodied understanding of their size.

2.2.1. Visitor Interactions and Gesture. Hindmarsh and Heath [2000] describe how gesture serves as embodied reference in a workplace setting. Heath and vom Lehn [2004] found similar roles of gesturing in museum conversations between visitors, where people used body posture and movement to discriminate objects, negotiate what to look at and how to look at it. They describe how this kind of gesturing, in concert with talk, reveals, highlights, and animates aspects of the exhibit, while remaining peripheral and subservient to the object, as a form of mediation. The gesture is "designed" to attract attention to the objects' details, and not to itself "seen, but unnoticed." Visitors, through talk and bodily behaviour "animate exhibits, highlight particular elements and dramatize certain features" [Heath et al. 2002a; Heath and vom Lehn 2004; vom Lehn et al. 2007]. Recipient design is evident when participants display their actions in an exaggerated way, not only to explain and support awareness, but often also to entertain their comrades.

Heath and vom Lehn [2004] provide an example that could be described as indexing actions, of a visitor using gesture to tie their verbal descriptions to the object while encouraging the other to look at this object more closely. Similarly, in a study of the "Deus Oculi" installation, which has hidden cameras in handheld mirrors next to a painting, visitors point between the mirrors and the camera picture that is embedded in the painting, "demarcating a connection" [Heath et al. 2002a]. Visitor interactions seem to have very similar characteristics regarding the use of gesture as workplace interactions, with some additional elements of mutual entertainment.

Moreover, Steier [2014] argues that visitor's mimicry of the pose of paintings or statues is similar to iconic and mimetic gesture and functions as a form of embodied interpretation. It helps the visitor to understand the artwork's expression (internal interpretation) and to communicate this to their companions. This idea for art interpretation has recently been utilized in the "strike a pose" kinect-based installation at the Cleveland Museum of Art, which invites visitors to imitate photos of artwork.[3]

In our earlier research [Halloran et al. 2006; Weal et al. 2006], we noticed the importance of pointing behaviours in the practice of visitor guides. Curators giving tours of a historic house's gardens frequently pointed out objects in considerable distance, in particular, to emphasize views and vistas. Often, pointing not only induced a reference to something "over there," but included a reference to "here": "from *here* you see. . ." Pointing and gesturing here are an important part of the explanation. In terms of the notion of indexing presented in this article, we can argue that talking about a building

[3]http://www.clevelandart.org/gallery-one/interactives.

visible at the very end of a wooded avenue indexes between the here and the there and makes us project and imagine. Curators are skilled in accomplishing these indexing acts to direct their audience's attention. The guides' pointing movements often were exaggerated and extended, demonstrating explicit recipient design, taking account of the configuration of bodies and environment, establishing and directing attention, timing explanations with gesture, and making sure the audience could see the pointing (cf., [Goodwin 2000; Hindmarsh and Heath 2000]).

3. INDEXING ACTIVITIES WITH AND AROUND MUSEUM INSTALLATIONS

We now return to our empirical work in the museum domain, starting with one detailed case study, which introduces the notion of indexing, followed by shorter examples. In all of these, dedicated installations relate to and augment existing museum artefacts or specimen. We understand these as spatially embedded technologies, given they are physically set up so as to relate to their environment and only convey their full meaning in this context. This kind of embedded technology supports indexing activities by visitors, who discover and highlight the relations between the installation and the museum environment to each other.

This design strategy relates to concerns in museum research and practice (discussed in the literature review section) about installations that divert visitors' attention away from the "real thing" and the aim of augmenting exhibits so that visitors can focus on the authentic exhibits [Ciolfi and Bannon 2002; Economou 2010; Kelly et al. 2004] and encouraging them to make connections [vom Lehn et al. 2007]. As we will discuss towards the end of this article, we believe this design approach to be relevant beyond the museum domain. While we begin with two successful example of embeddedness to give depth to the notion of indexing, some of the later shorter examples provide additional insight into design decisions that may affect the degree of spatial embedding, and thereby, may support or hinder people's indexing activities.

The first two installations serving as case studies, the Jurascopes and the Magnification Lens Table, are located in the Museum of Natural History in Berlin. The data material used in the current article originates from a research study that investigated several novel installations in this museum [Hornecker 2008; Hornecker 2010a]. A further set of shorter case studies discusses installations in the Glasgow Riverside Transport Museum, which was (re-)opened in 2011. Each museum and the installations are introduced in the respective sections, along with the study and analysis approach. In general, these utilize naturalistic research methods based on field-visit observation and video interaction analysis. Details of the study and analysis approach for each case study or set of installations will be discussed early on in the respective sections. Moreover, some insights into design rationales and development process of all installations could be gained from discussions with either the company that had developed these or curators that had been involved in this process.

3.1. The Jurascope Case Study: Seeing Dinosaur Skeletons Come Alive

Social interactions play a big role in how people experience the museum visit [Falk and Dierking 2000; Kelly et al. 2004]. The following study of museum installations in the Museum of Natural History in Berlin aimed to contribute to an understanding of how different technologies and designs shape people's interactions and support sharability [Hornecker et al. 2007], co-experience [Battarbee 2003] and shared experience [vom Lehn and Heath 2005]. In the current article, the focus is on indexing behaviours. In the following, we introduce the museum and the study, explain the Jurascope installation, detail study and analysis approach, and then, move to observations.

The *Museum für Naturkunde* is one of the world's largest natural history museums. It is famous for its display of gigantic skeletons of Jurassic dinosaurs, the object of the

Fig. 1. The majestic dinosaur skeletons in the main hall. One set of Jurascopes is set in the far right corner, barely visible in this photo.

installation discussed next. As part of its renovation and refurbishment (2005–2007), a number of novel interactive installations were installed, most prominently a set of media-augmented telescopes, called Jurascopes,[4] and an interactive multi-touch table. During analysis of field study data, the importance of spatio-contextual embedding became apparent. It revealed a stark contrast in visitor behaviour around the multi-touch table [Hornecker 2008], which related to its surroundings only on a very abstract level, with that around the Jurascope installation [Hornecker 2010a]. The table, despite extensive content of quiz-like questions and related answers, evoked almost no conversation and was explicitly criticized by some visitors talked to as "decontextualized." In contrast, rich social interactions emerged around the Jurascope installation and visitors creatively and conversationally engaged with its contents. It was carefully placed in sight of the related physical exhibits, and frequently, had its users refer back-and-forth between the screen contents and the museum artefacts. Close analysis of the data revealed numerous instances of what in this article is termed "indexing," which people seemed to engage in very naturally, sometimes in rather playful, explicit ways. Another installation that also evoked indexing behaviours, the magnification lens table, will be discussed later in this article.

3.1.1. The Jurascopes Installation. The sight of seven huge dinosaur skeletons immediately enthrals visitors entering the large entrance hall (Figure 1). The Jurascopes in this room are designed to create a link between the skeletons and the virtual reconstructions and 3D animations familiar from TV. This link is enforced through visual alignment with the skeletons present in the hall. The Jurascopes are based on the metaphor of a telescope (similar to the coin-operated tourist telescopes on mountaintops and castle towers, [see Figure 2(b))], and offer a window through time, using a combination of photos and animations. When visitors look through the viewer, they first see a photo of the hall with the skeletons in it. By turning the telescope on its base, they navigate and select a dinosaur skeleton. This starts the animation. First, inner

[4]Jointly developed by the German media design company ART+COM and the WALL AG.

Fig. 2 (a) The Jurascope installation, with three telescopes lined up on the left and a screen on its right side is located in a corner of the hall. (b) A visitor looks through a telescope at the skeletons.

organs appear in the skeleton, and muscles and skin grow [see Figure 6(b)]. Then, the background of the hall fades over into a view of a natural environment, and the animal starts moving, feeding, and hunting. Sounds from the environment and animals can be heard. Sometimes the animal seems to notice it is being watched, coming closer to glance at the observer or threaten them [see Figure 3(a) and (b)]. Each animated sequence lasts about 30s. Then, the dinosaur moves back into its original pose, freezes, and reverts into a skeleton again. The animations, thus, seamlessly loop back to the photo of the hall.

Two sets of Jurascopes are each positioned in diagonally opposite corners of the hall. Each focuses on a few skeletons in good view from its position. A large screen is embedded at an angle into the floor on the right-hand side of each set [Figure 2(a)], intended as a barrier-free version for wheelchair users and children (as explained by museum curators and design company staff). Here, dinosaurs are selected by turning a large lever next to the screen [Figure 5]. The screens have come to play a much bigger role than expected, attracting crowds. Both installation types are arranged carefully so that the visitors can see the skeletons from the same viewpoint as in the animations [Figure 6(a) and (b)]. In the remainder, the two variations of the installation are referred to as *Tele-Jurascopes* and as screens, or, together as *Jurascopes*.

3.1.2. Study Approach and Data Analysis of the Berlin Study for the Jurascopes. The Berlin study utilized naturalistic research methods, adopting a rapid ethnography approach and drew upon principles of ethnography and video interaction analysis [Blomberg et al. 1993; Jordan and Henderson 1995; Knoblauch 2005], starting from open-ended observation and iteratively evolving issues for detailed analysis. Such a "focused ethnography" [Knoblauch 2005], where short field visits complement detailed analysis of video collected on-site, is appropriate if the researcher is already structurally familiar with the setting and analysis focuses on selected aspects of a field, such as situations, interactions, and activities. The field visit then supports interpretation of video data, providing context and first-hand experience of the setting.

Field visit observations were conducted over seven full days in summer 2007. The observer focused on two large installations (an interactive table and the Jurascopes) but spent time throughout the museum to gain a sense of visitors' experience and behaviours around different types of exhibits. This was particularly useful in comparing behaviours, identifying patterns and variations, as well as gaining a sense of how different museum spaces affect atmosphere and interactions. Extensive fieldnotes taken on site documented the observed activity around installations and conversations overheard. Supplementing fieldnotes, a photo documentary was collected, enabling further analysis, e.g., of patterns of visitor positioning and postures. Since the museum does not prohibit photography and many visitors take photos, photo documentation could be done unobtrusively, blending into the "normal pattern" of visitor activity. The museum was very busy due to it being school holidays, further easing unobtrusive observation.

Fig. 3. (a) Children at the screen, seeing the skeletons in the hall and (b) an animation of Allosaurus in threatening pose.

Due to privacy regulations, video recordings were limited to short recordings focusing on installation screens with a handheld camcorder.

To gather more detailed data, five volunteer visitor groups were shadowed during their entire museum visit, video recording all events around interactive installations. This included families with children, groups of young adults, and retired adults with their adult children. The researcher accompanied these groups for 1–3 hours, requesting to be treated as a "friend of a friend" who tags along. The groups quickly grew used to the camera (which focused on the installations and the volunteers), often seemed to forget about it, and began to treat the researcher as a companion (the researcher was only allowed to record the volunteers for privacy reasons). This resulted in around 90 minutes of video at total from the Jurascopes that were fully transcribed, and then, analysed, oriented by principles of qualitative video analysis [Jordan and Henderson 1995; Heath et al. 2010]. The researcher immersed herself in the data via repeated viewing and transcription. Recurrent patterns of behaviour as well as interesting episodes were identified from the annotated transcripts and themes iteratively developed. These themes were first presented in Hornecker [2010a]. Following the original study, findings on the Jurascopes and the interactive table were presented and discussed at ART+COM; this provided additional insights into the design rationale of these installations.

For the current article, the data have been reviewed again, focusing on indexing behaviours. Video segments were repeatedly viewed, often in slow motion, and all incidences of indexing transcribed in further detail. In the presentation of vignettes in the following, some of this has been summarised and condensed again to save space. All dialogue has been translated from German by the author.

3.1.3. Two System Versions: A Shared Versus a Solitary Immersive Experience. Telescope and screen-based Jurascopes both deliver the same content and are contextualized in similar ways. This provided a unique opportunity to compare how installation design, physical setup, and shape influence visitor experiences and interactions. The form factors and interaction mechanisms of the telescope-like Jurascopes [see Figure 2(a) and (b)] and the screens [Figures 3(a) and (b) and 4] each resulted in a different type of user experience, and different interactions evolving around each. Its designers described the screens almost like an after-thought as a barrier-free version for small children and disabled users. In terms of technology and interaction design, the telescopes initially appeared much more interesting. But observation revealed a much richer (and more social) ecology of interaction emerging *around* the screens.

The two versions of the system provide very different experiences. The telescope [Figure 2(a) and (b)] blocks out the real environment and provides a very immersive experience, allowing for "suspension of disbelief," evidenced in explicit comments of

Fig. 4. The screen provides a social experience and offers space for a large number of people.

observed visitors and their direct reactions (e.g., flinching on being growled at by the approaching Allosaurus). But because the telescopes are designed for one person, it is difficult to share the experience. Even if an observer might guess what the telescope currently points at (which is not easy, as it only slightly turns around its base), the details of the animation are not accessible to them. This is reflected in a lack of conversations at the telescopes. Usually, companions do not know what a remark is about, and thus, do not respond to communication attempts.[5]

The screens, on the other hand, provide a very social and shared experience. They tend to be surrounded by a crowd (typically of 6 to 15 people) composed of multiple subgroups [see Figure 4]. People are not just waiting, but actively watching and commenting on what is going on, or try to scaffold and negotiate the use of the selection lever. Observation found conversations to emerge not only within but also across groups. In particular, adults have educational conversations with children and direct their attention, e.g., pointing out which skeleton in the hall relates to an animation. This is typical of family conversation in museums, where parents pose and answer questions, point out interesting things, and guide children's attention [Kelly et al. 2004]. This relation often is turned around, children showing off their knowledge of dinosaurs.

The Jurascope installation as such is not very interactive; it allows choosing and watching an animated movie from a few alternatives. Nevertheless it is very successful. Part of this can be attributed to the content design, with short animations holding children's attention, to well-chosen stories full of surprise, drama, and humour, and very explicit mappings to the skeletons in the hall. Moreover, the physical setup of the screens allows for a *shared experience*. The display setup maximises the number of people able to view, while accommodating children [Figure 4]. Engagement at the screens manifests in rich interactions not only with the system, but, more importantly, between participants and *around the system* [cf., Fernaues et al. 2008; Heath et al. 2005; Hornecker and Buur 2006]. Conversations explicitly or implicitly refer to the system or its content, commenting on, narrating or enacting animations. Overall, the careful placement of the screen in relation to the exhibits, at a low-angled level, along with the tangible lever control [Figure 5], enables groups of strangers to mutually orient to the screen and to communicate, negotiate, and enjoy themselves.

[5]Hornecker [2010a] provides more detail, including transcript examples demonstrating futile attempts at communication as well as further detail on the difference in social experience.

Fig. 5. (a) and (b) The lever provides a legible mapping in two ways: it has to point in the direction of the skeletons in the hall (and discernably latches into its settings) and the images on the support base resemble the outline of the dinosaurs. The lever furthermore tangibly externalises control (see [Hornecker 2010a]).

Fig. 6. Alignment of views: (a) view when looking from the screen towards the skeletons and (b) the screen, with the front skeleton (Diplodocus) being "fleshed out" to come alive. (Photos were not taken for this purpose, thus alignment is not perfect).

3.1.4. A Contextually Embedded Setup in Support of Indexing. The Jurascopes are designed to link between the original skeletons on display and animated clips of dinosaurs. The installation is located quite unobtrusively in the corners of the hall, and has a "serving function" to exhibits according to its designers. It is carefully embedded in the hall, making visitors look out towards the skeletons in direct line of sight [see Figures 2(b) and 6(a) and (b)]. The animations are thus contextualized through a meaningful spatial setup. The gradual build-up of animations starting with the "naked" skeleton further supports visitors in understanding the relation to exhibits. But rather then indexes being explicitly provided by the installation, people need to discover this relation and do the indexing. The installation merely allows and supports this by virtue of its positioning. The animation then is not just another movie, but enhances visitor's perception of the exhibited skeletons.

The video data yield various examples of children and adults indexing to the skeletons and between depictions on-screen and the skeletons (verbal or non-verbal). Many incidences at the screens exemplify communicative pointing and indexing (which at the telescopes is rare due to the difficulty of sharing experiences), but some also seem to primarily serve individual cognition. The following set of vignettes focuses on communicative situations involving indexing. In the first, a child points out which skeleton in

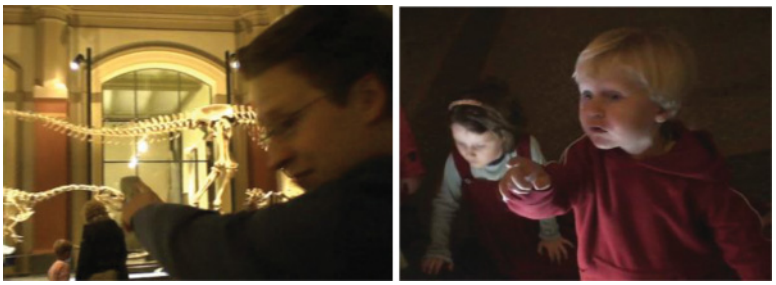

Fig. 7. Pointing and looking back-and-forth. Left (a) The father explains: "These are the dinosaurs from the movie (points at skeleton)—the small one was being chased." Right (b) The son looks up from the screen to point into the hall after seeing the animation and exclaims: "There it comes again: THE BIG one!"

the hall the current animation relates to ("over there"), indexing with words between screen contents and surroundings (the video at this point only captured the screen, so we do not know what bodily actions accompany this, if there is, e.g., any pointing). The vignette further demonstrates how an adult uses the opportunity for educational conversation, categorizing the dinosaur as a carnivore.

> Allosaurus is seen on screen, munching on the detached leg of another dinosaur. A child says "Look, that's the one over there." A male adult explains: "that's a carnivore."

In the following vignette, a female adult (most likely the mother) points at the screen, and then, up into the exhibition hall and back when explaining to a child.

> Mother to daughter: "Look these animals." (*In parallel: a woman talking to other children*) The daughter replies: "Yes, the other one."
>
> Mother continues: "Look, now this animal comes (points at a dinosaur getting fleshed and growing skin on-screen) and it stands there (points into the exhibition hall towards the skeleton displays), and this is how it lives in nature."
>
> The new dinosaur is getting skinned up in the animation. (. . . *omission* . . .)
>
> A few seconds later, mother: "That is the same again, the long one here (her finger points at the screen, then up over its rim into space), the one with the long tail. That way you can compare it."

Here, the adult utilizes the possibilities that the animations and the spatial setup of the installation provide her with, to emphasize how animations and skeletons relate, and to explicitly invite the child to "compare." She indexes via language (this, there, here) and fingers, pointing. It is notable that she not only indexes from the screen to the room, creating a relation between the animated dinosaur and the skeleton, but then also indexes *back* to the screen ("and this is how it lives in nature"), emphasizing that the animation shows the natural environment.

The following transcript of a longer sequence from a shadowed family provides an example of how very young children already begin to understand the relationship between the skeletons and animations, and how parents emphasize and reinforce these connections [see Figure 7(a) and (b)]. When this group, consisting of father, mother, their 3-year-old son Bob and a 4-year-old daughter, had entered the room, the children immediately responded to the skeletons put up in the middle of the hall, exclaiming: "it's huge, this one". The parents explain how archaeologists dig up the bones, clean them, and then, put them together again. They then walk the children

to the Jurascopes. At the point where the next vignette starts, the family has already spent a considerable time at the screen, watching the animations. They frequently replay clips, with the two children, who kneel at the screen, sharing control of the lever. So far, the screen has transfixed the children who almost seem to have forgotten about the real skeletons that initially drew their attention on entering the hall.

> The family watch a clip with a very long and big dinosaur on the screen. As the animation finishes, Bob points at the dinosaur skeleton and exclaims loudly: "The GIANT DINOsaur!" (. . . . . .)
>
> The father suggests going to the other screen on the diagonally opposite corner and they begin to make their way through the hall. As they walk past the skeletons in the middle of the hall, he tells his son: "And these are the skeletons to it. They were soooo big!" The daughter (running behind them) repeats: "They were so big." (. . . . . .)
>
> After having watched the animations on the other screen for around 5 minutes (they are fascinated, like most children, by the Allosaurus), the boy walks away and his father follows him. He asks his son "can I show you something?" and tries to take him by the hand, but the boy already marches towards a number of large skeletons in the corner of the hall (which were the content of the animations from the previous screen they were at). The father reaches out to Bob, tapping his shoulder, and then, points forward: "Look, that's the dinosaurs from the film." They slow down, approaching the barrier, and the father bends down to his son.
>
> Crouching down to Bob's height, he then points straight up at a large skeleton, looks up, then down at Bob. As Bob looks at the skeleton, the father lowers his arm: "Look, Bob, the big one? That's the one (he points at its head) that yelled at us. See, this one roared at us" (he points towards the right, up at an Allosaurus, now kneeling next to Bob). Bob agrees: "Yeah, it was . . . (three incomprehensible syllables)" and his father expands: "it was eating a dinosaur's leg. And this small one (he points at a small skeleton directly in front of them) was being chased - (he points to a third skeleton on the left) this was a predator, this one chased this other one" (he now points from the leftmost the middle dinosaur skeleton).
>
> The boy walks away and the father follows. They reach the first screen again and, again, look at the animations running. Father and son are in conversation most of this time. An animation starts. Bob, who has been kneeling before the screen so far, comments: "there's the big one again". Then he stands up and points into space while tilting his head back, shouting: "There it comes again: THE BIG one" [Figure 7(b)].

This vignette features a series of cross references, initiated by the son pointing at the dinosaur. The children are fascinated by the size of the dinosaurs, and their father uses this in the following interactions to draw the children's attention. He emphasizes the dinosaurs' size as they walk right next to a skeleton that towers over them. On both ways past the skeletons he "indexes" back to the animation (verbally, as the screens are not present), and on their return from the other screen he recalls details of the animations. The children react both times, looking up and repeating statements like "so big." Most of the indexing actions so far indexed over time, back to a previous experience (at the screen, or looking at the skeletons). When back at the screen at the end of the vignette, watching the animation, the son demonstrates that he remembers this is one of the huge skeletons they looked at. Making these references is supported

Fig. 8. (a) and (b) Two visitors are looking back-and-forth between the telescope view of the dinosaurs and the skeletons in the hall.

by an uninterrupted visual flow on the walk from the screens past the skeletons and back.

In the following, the focus is on indexing without a clear communicative purpose. At the Tele-Jurascopes, verbal and gestural references aimed at others were rare. Instead, bodily behaviours indicate that there is also non-verbal indexing in support of individual cognition and perception. Given the animations are understandable fully on their own, it seems remarkable that people were nevertheless seen to glance back into the exhibition hall, comparing and searching. A methodological difficulty in analysis of this non-communicative behaviour is that it tends to occur in silence, providing very few explicit clues on internal processes. Our data for this behaviour are, therefore, admittedly scarce.

In the following vignette, John repeatedly glances over the viewer towards the skeletons before turning the telescope, using the real exhibition hall for reference and overview of choices [see Figure 8(a)]. Towards the end, a rare example of communication at the telescope occurs, which is successful because John's friend used the telescope earlier.

> John takes a position at the telescope and quietly looks into the viewfinder (we can only guess that he is most likely watching one of the animations). Half a minute later, he briefly glances back at his friends, and then, continues to watch in silence. After 10s, he briefly looks up, and then, readjusts his head to the telescope, watching quietly again, while his cheeks are chewing (gum?).
>
> Another 12s later, he suddenly stretches his head up and looks over the viewfinder into the great hall (for roughly a second, very focused), and then, looks into the viewfinder again. He watches for another 30s in silence (the typical length of a clip, so we can assume he finishes watching an animation). Again, he has a glance over the viewer towards the skeletons, and now turns his head to the far right, looking out into the corner of the hall [Figure 8 left], possibly checking if there are other skeletons, before he turns the Jurascope towards the right. He turns the telescope while moving his head back to the viewfinder.
>
> A bit later, a friend asks: "Do you have the one on the far right now"? John answers without looking up: "Mhhh, the left one. From these (gestures to skeletons) the two, you see them skipping around."

From his visible concentration, calm pose and quiet watching, we can infer that John is acting purposely; there are no indicators of confusion. John's glances over the telescope are an example of a very subtle form of indexing, which is identical with the perceptual act of the glances, but still serves the making of connections. It is notable how he (and others, like the lady in [Figure 8(b)]) appears to utilize the exhibition hall to gain an

Fig. 9. This sequence takes place over about 15s. This boy, standing at the lever, silently glances up and down, comparing between the skeletons in the hall and the Jurascope screen.

overview and to search, and is not content to just explore the animated content. Instead of simply turning the telescope to the far right, he first looks into the hall, and then, moves the telescope in the same direction, using the hall with the real skeletons as his frame of reference. From a distributed and extended cognition viewpoint, there are multiple advantages of switching back-and-forth between telescope view and real environment. Turning the telescope changes the augmented view, and thus, creates a change of state, while the bodily movement is more easily reversible—there may be less perceived cost of action. Moreover, the telescope only shows a small angle view, whereas the human eye has a wider overview. In addition, the telescope allows John to "freeze" one view, while freely exploring another perspective. This enables him to switch between two representations, one of them being the real world, and the telescope serving as a kind of "pointer" onto the other. We thus can see elements of "epistemic action" [Kirsh and Maglio 1994], and of John using the world as a representation of itself, fluidly switching and cross referencing between two views.

These kinds of back-and-forth glances also happened at the screens, both by adults and children. In another example at the screens [see Figure 9] this kind of indexing without communicative intent is apparent from the nonverbal behaviour of the child operating the lever. The boy is currently in control over selecting a dinosaur and has done this for several sequences already. He guards the lever from interference by other children by keeping his hand close, and has already learned to wait for the end of the animation until moving the lever again. His actions are very similar to those of John glancing over the telescope. Within about 15s, he repeatedly glances down at the screen and up into the room towards the dinosaurs, apparently comparing the depiction on screen with the contents of the room. The movements are subtle, as he mainly raises and lowers his head, glances up and down as well as sideways, and in the final picture, his chin drops, and he leans forward, now focusing entirely on the screen again.

3.1.5. Reflection and Insights From the Jurascopes. These are just a few examples from numerous incidences of indexing observed in this study. Referencing back-and-forth between the dinosaur images and animations on the Jurascopes and the skeletons in the hall was a recurrent and almost ubiquitous behaviour. The example vignettes illustrate communicative indexing (the majority of found incidences) and indexing in support of individual sense making and planning. Both are engendered by the spatial setup of the installation, which aligns the depicted graphics with the real

Fig. 10. (a) and (b) The magnification lens table in front of the biodiversity wall glass case.

artefacts in one line of view and provides an uninterrupted experience. Communicative indexing is only effective at the screen version, where the content is available to a wider audience. Here, repeated indexing actions in conversations between companions and in educational exchanges between children and adults were observed.

In particular, the animations from the Jurascopes achieve a much richer meaning in the context of this setup, enriching visitors' understanding of the dinosaur skeletons in view and turning these alive. Seen on their own, they are merely nicely done, but fairly generic dinosaur movies. The Jurascope installation here thus serves as a prime example of "spatio-contextual embedded systems," from which we can begin to determine design considerations in support of indexing.

Factors that contribute to the successful embeddedness of this installation and the resulting indexing activities by users are that it is easy to relate both worlds. The lever at the screen can be turned and pointed, and is illustrated with outline images of the dinosaurs, providing a clear mapping (we will return to this again later in this article, see Figure 16(a)). Screen/Jurascopes and skeletons are carefully aligned in one line of view. On a content level, the animations enrich visitors' understanding of the exhibits—after watching them, one might look different at the artefacts. For social interactions, having mutual orientation and visibility of both users' actions and the screen contents (for the screen version) supports sharing of experience and enables bystanders to understand what gestures refer to.

3.2. The Magnification Lens Table: Wonderment and Indexing Effort

Figure 10(a) and (b) shows another installation from the Berlin Museum of Natural History. It consists of a wall-sized glass display cabinet with a table placed in parallel at about 3meter distance. The display wall shows the diversity of species and is next to a room dedicated to the theme of evolution. The room is only dimly lit. The animals are placed separately and are dramatically lit, but not labelled, a bit like a seventeenth century cabinet of curiosities. This setup invites marvelling at the beauty (or bizarreness) of animal life. The table surface shows a background-lit photographic reproduction of the wall with labels next to the animals. But the writing is not legible with the bare eye; instead, two large magnifying lenses are affixed on movable arms [Figure 10, right].

The lack of labelling at the display cabinet means that visitors rely on the table to identify species. This requires them to move back-and-forth, or to collaborate. During the in-situ study, some visitors were observed to spend extended periods of time, discussing animals. Sometimes one person would stand at the cabinet and ask another to read out names. A similar pattern as with the Jurascopes was observed, as people

Fig. 11. (a)–(c) Sally quickly looks up to find the animal, straightening up from a bent-down pose, mumbles: "Ah there" and bends down again, all within 4s time.

frequently looked up and down, sometimes sparked by the image on the table to search for the real specimen, sometimes searching for the name of a species that struck their curiosity in the glass case.

In the course of re-analysing the Berlin data, the video from this installation was reviewed given the installation can be considered another example of spatio-physical embedding, albeit without digital augmentation. The data (which had previously not been analysed in detail) have been subjected to the same kind of detailed, repeated viewing as for the Jurascopes and instances of indexing behaviours were transcribed in detail. There exists only limited data for this installation, with half of the shadowed groups spending time here (public recording was not allowed due to privacy regulations), and the distributed setup made it difficult to capture people's orientations. Still, the captured interactions reveal several incidences of indexing.

Figure 11(a) and (b) shows a 4s sequence where Sally stands alone at her side of the display table. She looks down into the lens (first image), then raises her head while remaining in this bent down position. A moment later, she straightens up (middle) while keeping the lens in place, and stand stills for a moment, saying "Ah, there" to herself (indicating she was searching for the specimen corresponding to her lens focus in the cabinet) and bends back, looking into the lens again [Figure 11(c)].

This sequence is similar to the occurrences of "indexing for one's own" observed at the Jurascopes, in that the solitary indexing activity consists of glancing back-and-forth. The lens, similar to the telescope of the Jurascopes, externalizes the point of attention on the table, embodying the possibility to look back (note how Sally's hands keep holding tight on the lens while she looks up).

This pattern of looking down and up, bending down and straightening to then bend down again, also occurred with the other groups shadowed and recorded during their visit, sometimes also evident from participants' body leaning towards the left/right when looking towards the display cabinet. In the following vignette, we see a pair of young adults shifting attention between the table and the cabinet and helping each other. Here, the situation develops from individual to communicative indexing.

> Anne and Ben stand at the table. Anne holds the lens in both hands and looks down, while Ben looks over her left shoulder. Ben leaves and walks towards the cabinet. Anne looks up, staring intently towards the cabinet. After about 2s, she looks down at the table again and moves the lens.
>
> Ben approaches her again from the other side of the table, briefly touching her arm to grab her attention: "Anne." He moves a step forward and points to the glass case: "those critters over there (he points extendedly), . . . this thing" (hand stretched out pointing). She replies: "next to the spiders" and he confirms: "yes."

> Ben returns, now joining Anne at the lens behind the table. He points at the animal depicted on the surface, and explains something in a low voice, while Anne moves the microscope arm. He helps drag the lens in place, then bends down to read aloud: "horseshoe crab." They both look up again, and Anne's hand on the lens loosens its grip.
>
> A while later, Anne moves from the table to the glass case, and after a few seconds, Ben follows her. Anne kneels at the glass case to inspect an assortment of insects, they talk, and then, leave in search of the rest of their group.

In the first paragraph of this vignette, Anne looks up and down, apparently trying to draw connections between the table image and the glass case. After looking over her shoulder, Ben goes scouting, explores the physical display and comes back (second paragraph) to find out what one of these, which caught his attention, is—apparently he knows it from vacations in Asia, as a later dialogue between the two indicates. In the second paragraph of the vignette, Ben helps Anne find the animal by pointing at the glass case (with stretched out arm and hand), having difficulties to explain "those critters over there—this thing ...." Once they have jointly established the object of interest, they both focus on the table again, and he points at the animal depicted on its surface, and subsequently, reads its label.

As described in the analysis of a similar sequence by Heath and vom Lehn [2004], Ben and Anne spend considerable energy in negotiating alignment of attention. What is notable here is that Ben wants Anne to first find and note the real specimen inside the glass case, even though this is bound to take some time and effort, instead of just pointing at it on the table (his later action reveals that this takes little effort). Ben not only indexes for himself, but makes sure that Anne can draw this connection as well. At the end of the vignette, both return to the physical display case.

3.2.1. Reflection and Insights From the Magnification Lens Table. While not used by large numbers of visitors, those observed here seemed to enjoy it, often spending considerable time at the table. One criticism was font size (too small for older visitors despite the lens). Some visitors pointed this installation out as more interesting than the interactive multi-touch table close-by which supports an information browsing activity, but does not give users much control over the flow of activity, with no ability to delve deeper into a topic (cf., [Hornecker 2008]). Based on overheard conversations and debriefing discussions with some of the groups shadowed for the overall study, the contents of the multi-touch table are perceived as random and unconnected by visitors. Moreover, it does not relate to any of the objects in its direct surroundings. Observation and recordings reveal almost no discussion about the displayed content, and visitors seem puzzled as to "what the table is about." This is very different from the focused, intense engagement observed at the magnifying lens table. One of the shadowed visitors commented "This thing is super—first I thought—why do they have so many of these critters in there and you don't know them at all, and no labels at all." The installation initially puzzles people, and piques their curiosity once they detect the lenses and text on the table. The effort that they need to invest often appears to result in deeper sense-making activity. But this also indicates a trade-off, as some visitors may not notice the lenses, and leave the room somewhat confused about the lack of labelling.

There are probably two qualities to the magnifying lens table in combination with the large display case that make this an engaging experience. First, the display case enables visitors to view animal species almost like an art piece, wondering and marvelling. It removes the distraction of "labels," creating a sense of mystery. Secondly, it requires work and energy to find an animal's species name on the table. Concentrating on, and navigating the lens around the table, results in very conscious acts of indexing,

of moving back-and-forth between the more abstract (and tiny) depiction on the table and the full-scale animals in the case. Some people seem to enjoy the search effort required.

This installation is very different from the Jurascopes, which only relates three to five easily distinguishable dinosaur skeletons and where the animated movies are the main content that people focus on. But even with the Biodiversity wall and the table, the relation is always clear, there is a clear line of sight and the cabinet is close enough to identify the object's approximate place. While feasible, one needs to invest effort and time, which brings the indexing activity into the foreground of attention. Nothing in the installation rushes the visitor; the setting rather calls for focused attention and marvelling. As with the Jurascopes, the magnification table on its own would not hold the same attraction and sense of wonder—it clearly has a serving and enriching function for the glass cabinet and only achieves its full meaning in its context. Different from the Jurascopes, this installation requires significant effort from visitors to draw connections.

3.3. Further Examples from the Design Space of Spatio-Contextual Embedding

In the following, we present a further four examples, illustrating a broader range of attempts at spatio-contextual embedding with various success rates. Interpreting spatio-contextual embedding as a design space, examples provided so far only pinpointed a few aspects of this design space, and illustrated successful designs. A comparison with further examples, including less successful designs, may reveal issues that remain implicit, and therefore, invisible in successful designs and may point out potential design strategies and challenges.

All installations discussed in this section are in the Riverside Transport Museum in Glasgow, which our group currently collaborate with in the context of a Ph.D. project (see [Clarke and Hornecker 2013]). An initial survey of candidate interactives for further detailed study within this Ph.D. had us notice several systems that varied in success of spatio-contextual embedding. The most interesting ones in the context of this article are discussed here.

The Riverside museum houses over 20 interactive hands-on installations, including at least five multiplayer games, and a similar number of hybrid interactives in addition to 90 touchscreen panels and several immersive video and/or sound installations, most being very innovative and well-liked with visitors. It won the 2013 European Museum of the Year Award and is one of Scotland's favourite museums. The museum is notable for its approach of conceiving installations in-house within the curatorial team, and working closely on their realization with contractors, based on an in-depth brief. Curators create detailed interpretation plans that specify the target audience, define the core "story" and message, desired learning outcomes in terms of knowledge, skills, values, and attitudes, desired user experience in terms of creativity, inspiration, and enjoyment, as well as visitor behaviour (e.g., collaboration and coordination between group members, or playful competition) (see [Clarke 2013]). Every display is developed for a particular audience (families, under-fives, school groups age 5–14, teenagers). As part of the initial design process, paper prototypes are often created, if feasible in real scale, to gain a sense of how exhibits will look on the floor, and potential users (e.g., school groups) are invited to test them. Even with this careful design process, there are limitations, e.g., technical difficulties and insufficient resources for physical prototyping of non-screen-based exhibits [Clarke 2013], or, as with one of the installations discussed in the following, the support of indexing may come as a trade-off with other relevant design aims. It should be noted that the installations discussed in the following were intentionally selected to illustrate some of the challenges in developing embedded installations, and thus, are not all representative of the overall museum.

Fig. 12. (a)–(e) The ship conveyor belt. Top left (a): View of a subsection of the large window, showing the conveyor mechanism. Top right (b): A more detailed view with one screen visible in the middle and a woman on a bench. Bottom left (c): A family watching the ships and one screen (the adult looks at the screen). Bottom middle (d): A ship passes over a screen, showing its name, history, and size. Bottom right (e): Further examples of screen information (details of ship and shipyard it was built).

A limitation of the following discussion is that it is not based on as systematic and lengthy a study as the previous two case studies. The analysis is based on first-hand experience of using the installations (in a pair of researchers), joint reflection on this experience, as well as observations and fieldnotes. Informal observations were conducted during the initial survey of all interactives. Moreover, whenever visiting the museum for meetings or other occasions (in the context of the on-going collaboration, which is outside of the scope of this article), the author took effort to observe visitors at the installations discussed here.

The first of the installations discussed in the following is the Ship Conveyor. It serves as another example for successful "embedded" design, and has been the object of more detailed study because its rather unusual design struck our attention. The other three installations illustrate challenges and trade-offs for embedded design. The discussion of these installations is largely based on informal observations and first-hand experience by the author and her team. Due to our close collaboration with the museum, we obtained insight into the overall design process utilized for creating new installations and could interview the Riverside's/Glasgow Life's New Media curator about the installations, enquiring about the original design rationale and process and discussing our own observations.

3.3.1. The Ship Conveyor—Spatio-Temporally Contextualized Displays. One of the smaller rooms on the upper floor has models of ships built in the local shipyards move on two conveyor belts through a large window, coming in from the left on the back of the case to the right and looping back in a U-turn [Figure 12(a) and (b)]. The left half of the loop is hidden from sight. Seven LCD screens are located inside the window so that the models pass in front of them. A few seconds before a model reaches the screen, information about the ship is displayed (significant facts), i.e., where it was built (a map with a pointer to the shipyard), and basic information such as name, size, type,

and usage classification. Then, further screens show detailed close-ups and information about the ships' working life (where and what for used) [Figure 12(d) and (e)].

Our initial observations indicated this installation as an excellent example of successful spatial embedding. As part of the mentioned Ph.D. project, we have observed activity in this space on various occasions, totalling over 6 hours of in-situ observation by a team of two researchers. Here, only indexing aspects are discussed.

The Riverside curators identify this as their second most popular exhibit. Our observations confirm this to be a very popular space, where visitor groups spend substantial time, standing before the large window display, talking about the ships, and apparently like to see again on return visits to the museum. Part of this has to do with the role of the Clyde shipyards for Glasgow heritage—all the models represent ships built in the area. But not only local visitors congregate here, we also observed many foreigners.

The museum curators[6] classify this as a "high density display", which allows them to exhibit a large number of objects within a comparatively small space. A static display of ship models already was a popular part of their old building. This "dynamic installation" enables them to showcase more ships, as well as "going deeper with interpretation" since the seven LCD screens can show information about every ship without overcrowding the display case. Interviewed about the exhibit design, curators emphasize that the screens are "carefully spaced and placed" so as not to detract from the models. Besides of conveying more information, the design aims to get visitors close to the models and have them appreciate these as "objects in their own right." The display was originally aimed primarily at families and school groups, but seems to be of interest across all visitor types, with all age groups spending significant amounts of time here. A particular quality of this installation is its (intentionally) calm and ambient appearance, as the screen contents slowly transition and the ships gently float past.

The space is usually well populated, and visitors either stand close to the window, talking about the ships and reading information from the screens, or sit on the benches facing the display, enjoying the view of the ships passing by. People in conversation, closer to the window, frequently point at the ships and screens. Discussions often relate very closely to the ships and are triggered by information from the screen, e.g., about family members having worked at one of the shipyards. Also, adults read out screen contents, narrate, and explain for small children who tend to be highly attracted by this display. An example from our observational field notes illustrates these kinds of adult-child interactions.

> A group of small boys is fascinated by the ships. One especially likes the hospital boat. A male adult (possibly the father) stands at the screen at the far right of the window, watching both the children and the screen. As the boy walks next to him, he explains "that's the Brigadier ... 1966 (incomprehensible). This (points to the screen) shows you where it was built." He points out a few other facts about the next boat. Then, the boy excitedly runs after the hospital boat, which has already moved a few meters on, and the man follows him.
>
> A while later, the boy stands at the left side of the window with the other boys, staring through the glass. As the ship begins to approach them again (having done a loop in the meantime), the boy excitedly explains: "hospital boat—it is coming!" The boys now all wait for the boat, and stare at the screen, apparently expecting to see information about the boat on it.

The close vicinity of ship models and screens along with the temporal coincidence of the information shown with the ships' traverse seems to create a very legible relation

[6]All quotes about design rationale and process are from our interviews with curatorial staff.

Fig. 13. A game related to the old-timer "car wall." Top left (a) The car wall with three rows of cars. The installation is placed on an elevated platform. Top right (b) Children playing. Bottom left (c) Overall setup facing the rows of cars. Bottom left (d) Close-up of screen with the depicted cars moving along each row.

for visitors, with a clear spatial and time-based mapping. There is less explicit back-and-forth pointing at this installation than at the Jurascopes. This is possibly because everything is so closely aligned and co-located that visitors do not feel they need to highlight the connection. But we observed frequent glances back-and-forth and verbal reference to the text from screens, as well as pointing at either the ship models or the screen. For example, when the adult in the above vignette explains "this is the Brigadier" he does not need to point at the ship, as it is in direct sight and right next to the screen. Still, visitors have to draw the connection themselves.

The behaviour of the conveyor belt is predictable, but slow enough to read the screens (which only contain limited amounts of text), and gives visitors sufficient time to look back-and-forth. Moreover, we often saw people waiting eagerly for information about a particular ship to appear. Children would sometimes ask "what is this one" and adults would then ask them to wait until the screen shows the information, and then, read out its name or function. The slow pace of the conveyor seems to create a sense of anticipation that makes people linger, while providing ample time to discuss and share information. As in the previous examples, the screens only achieve their full meaning in connection with the ships passing by, providing contextualized information—contextualized in time and space in this case.

3.3.2. Three Multiplayer Games. Several multiplayer games invite visitors to playful activities that relate to the artefacts in view, and can thus be interpreted as attempts for spatio-contextual embedding. The game depicted in Figure 13(b) and (d) relates to the big show-wall of old-timer cars, arranged in three rows on a grid of shelving up to the ceiling of the hall [Figure 13(a)]. According to curators, it is aimed at encouraging

families to playfully engage with the exhibits in a musical game. Eventually, it was one of the first installations to be taken down, partially due to breaking down, but also since it did not achieve its aims.

On an elevated platform facing the car wall, four screens are mounted, each with headphones and a red motion-sensitive wand with a pointy ending affixed on a rope [Figure 13(b) and (c)]. Each player is allocated three cars, the left-most player with the left-most column on the wall, and so on. After players are introduced to their cars, they train to point/flick the wand in the direction of the cars on the shelves. Pointing at the correct car produces a sound effect (car noises, such as motors, doors closing, or brakes), which becomes part of the musical score heard over headphones. Once the game starts, images of cars move on three rows from the right to the left on the screen. To gain points, players flick the wand in the direction of the corresponding (real) car when an image of their assigned cars travels through the left column [Figure 13(d)]. The analogy here is with designated notes on a sheet of music that have to be hit as they come into view, similar to the Guitar Hero game.

The core idea of this installation as to the curators was to let visitors hear what the cars sounded like, and to have fun engaging with them. The game idea was developed with family groups (recruited from "friends of the museum") aiming at something that requires users to look and point at cars to trigger their sounds. In development, it was tested with paper cut-outs of the cars pasted to a wall, and appeared to work well, as test users understood and enjoyed the game. But testing was done with a scaled-down model at a fraction of the real size. Once ported into the new museum space, according to curators, its "usability plummeted, due to the sheer scale of the car wall—users could not make the link to cars at the extremes of the wall that they could only see from a far angle."[7] Figure 13(a) provides an impression of the dimensions.

Our own attempt at the game failed miserably. We observed other adults who were confused what to do and how, whereas children seemed to be happy playing with wands. While the game is intended for a family audience, only small children persisted, although they clearly struggled and showed no sign of understanding what the game was about. To start with, the playability of the game is hampered, as it is not easy to flick the wand in the correct direction and with the right movement. We can further identify a number of factors that prevent visitors from "indexing." Smaller children cannot see the cars on the ground level because the game screens obstruct their line of view [see Figure 13(c)]. This destroys the visual analogy between the three lines of cars on the screen and three rows on the wall. Moreover, the game can be played without looking at the wall once one has memorized the directions of where to wave. The activity thus does not result in or require *actual* engagement with the cars. Finally, the speed of the game does not leave time to look at the cars—it requires players to continuously monitor the screen. The game speed negatively affects resources for spatial orientation and for looking back-and-forth, especially since, at this scale, physical head movement is required (which is far slower than eye movement).

It is noteworthy that the game failed despite early user testing during design. That some effects can only be experienced (and tested) at the correct scale raises important questions regarding how to prototype such embedded installations given full scale prototypes are costly, and as in this case, can be logistically impossible.

Another common schema for relating an interactive display with a display of objects seems to be that of a quiz show. Quiz questions can ask players to inspect the objects and compare them. But do they promote real engagement with the content? The following two installations build on this genre.

[7]Personal communication, David Scott. Riverside Museum, Glasgow Life.

Fig. 14. (a) Set up of a multiplayer quiz game about motorcycles and (b) the player's screen. Note that there are two columns of motorcycle icon buttons on the left side of the screen and three on the right, but there is no button for the motorcycle located above the door that constitutes a gap between columns.

The multiplayer quiz game in Figure 14(a) and (b) relates to a wall of motorcycles in front of it and the core idea behind the installation design was to draw attention to these. The game is inspired by the British card game "Top Trumps" and intends to let visitors notice and think about the different qualities of the motorcycles on the wall in terms of price, performance, weight, size, and so on. The game was intentionally developed so that it cannot be played without the bikes for reference—players need to inspect them for clues. Up to four players can answer quiz questions, for example, "which bike has the smallest engine—tip: check the size of the engine under the tank" [see Figure 14(b)], while a timer ticks. Other questions ask to look for the oldest, lightest, or heaviest bike. Each player has their own terminal and players can join in at any time. The grid of buttons on the quiz screen corresponds to the grid of actionable bikes on the wall. Each player can only choose from a subset of bikes, which is randomly allocated at the start of the game (similar to a hand of cards). This is colour coded—each player station has a different colour (blue, green, pink-red, yellow) and the bikes are lit up in corresponding colours. On their screen, only the corresponding buttons are active (lit in the same colour). This means that if a player's station is yellow, they can only "play" yellow-lit bikes for a question, and thus, may be unable to provide the right answer even if they know it. After pressing an active button, the choice has to be confirmed: "Play bike." Once all players confirm their choice or the timer runs out, the correct bike is revealed, blinking on the screen, and a video about it is shown, while the lights on the wall blink to highlight the motorcycle.

When we first attempted the game ourselves, it took us several rounds to grasp the rules. Curators are aware that this game with what they acknowledge to be an "ambitious game concept" has a steep learning curve, but argue that repeat plays become more rewarding. It is intentionally aimed at repeat visitors, which make out a third of the museum's audience.

While we have not conducted systematic observations, we attempted to observe users on multiple occasions during our various visits at the museum. Different from high-frequency installations such as the ship conveyor, this installation was often unattended, or visitors left just as we arrived. On several occasions of informal observation we noticed that adults did not appear to understand what to do, and left after playing one question. Children and teenagers were quicker in comprehension, and sometimes played a couple of rounds. But we did not observe much actual conversation about the motorcycles, apart from quick guesses by those who had understood the game. In the following example (from in-situ note taking), some group members do not even realize there is a relation between the game and the bike wall until they leave.

> Two boys (at reading age) approach the stations. The two accompanying women (one mature adult, the other younger), upon being called, join them at the other stations, trying to play. They all stare down at their screens, as the timer runs down. One of the boys shouts: "press, you need to press." The adults do not seem to know what to do. Finally, on the players' screen one of the buttons is highlighted, showing which bike was the correct answer, and a video about it plays. The older woman says: "that's a bit weird." She begins to turn away from the screen to walk around the line of stations towards the wall of bikes. She looks up, and down at the screen again: "Oh, it is about the bikes that are here!" The group leaves, now walking towards the bike wall.

In this example, we see the adults being unaware of the relation to the bike wall until they have already left the game station. The boys, who already know how to play (it is unclear if they have played before the observer approached or are repeat visitors), follow the adults, who have not understood the game rules. Realizing the connection with the bike wall does not seem to motivate them to return to the installation. The vignette illustrates how a lack of visual alignment (and recognisability) along with the required cognitive effort may prevent visitors from even realizing that the game relates to the bike wall.

The installation lacks in "immediate apprehendability" [Allen 2004, Bitgood 2013]. Visitors do not immediately understand how to interact or see a reward for doing so. This learning curve can result in giving up on the installation. Three core issues are abstractness of mapping, rapid pace of the game, and the complexity of rules.

Several issues make this game hard to understand and make it difficult for users to deeply engage with the contents and the motorcycles. To start with, it is not straightforward to ascertain the mapping of icons to the bike wall. On the wall, there is a motorcycle placed on the fourth row, above the door, which is missing on-screen, and thus, unplayable [see Figure 14(a) and (b)]. The abstracted icons on-screen are all identical. For orientation, players rely solely on the 2D grid on both wall and screen (with one bike missing on-screen). This is different from the Jurascopes, where the depicted skeletons are each distinct in shape and pose, and users only need to select in left-right order. Moreover, the game mixes two genres, that of a quiz show and a game of cards where each player is dealt out a hand. Players might not be able to vote for the correct answer, lacking this card. This may be confusing for some visitors, and can be frustrating. In terms of cognitive demand, playing requires focusing on one's own colour (and not getting confused by the other lights), as well as identifying which row/column a motorcycle is in on the wall.

Moreover, the game is very fast. While the countdown runs, one needs to read the question on the screen, find the motorbikes lit up in one's colour on the wall, and identify the one that performs best regarding the question. Then, one has to look back at the screen and find the corresponding button from a grid of (non-descript) icons. The time provided does not really allow for looking back-and-forth several times. The game dictates the pace of interaction, and does not give players much time to inspect the wall. The pacing does not allow discussing, taking in new information, and relating to existing knowledge. Despite of a clear relation between the game and the motorcycle wall, this does not result in the type of active indexing, which this article began describing. Instead, there is a frantic search, trying to guess which relation the designers of the game intended.

Our next example illustrates another instance of the quiz-show concept, which fares pretty well, but also highlights a potential issue. The two-player game "wheels of fortune" was developed for school audiences and relates to a product design topic in Scottish curricula. Three screens are directly attached to a display case, making the

Fig. 15. (a) and (b) "Wheels of fortune," a multiplayer quiz game. Parallax issues: From the perspective of the left player (right image), the radio left of the dress is hidden from sight, while the right-hand player cannot see the little toaster on the left, which the left player is able to see.

connection evident [see Figure 15(a) and (b)]. A vertical screen shows a quiz host asking questions and counting down time. Players have to guess which of the objects in the display fit the description (e.g., which object has unusual colours?) and to select it on their screen. The game requires no prior knowledge of the original TV show "wheel of fortune." As curators explain, it prompts visitors to "think about how period design can influence domestic products," from cars to dresses, toasters, and radios, and to spot similarities (e.g., round shapes and streamlining). To answer, visitors need to study the objects in detail, some questions even require going up close, inviting assistance from companions. The game can thus turn into a shared activity for team play in school groups.

The mapping between screen and display case here is clear (icons are recognizable and the layout distinctive), and the small number of objects to pick from renders the game manageable. But there is a slight flaw in physical layout. From the left player's position, the big "quiz show host screen" screen hides the object to the right of this screen and the right-hand player cannot see the object on its left. The display case is about half a meter behind the big screen, and visual parallax takes effect. This highlights how important the physical configuration is to ensure that contextual references are possible. Tests, using a photo of the object wall, would not have revealed this problem—it would require a 3D model. In this case, the museum curators were aware of the issue—but changing the physical configuration would have significantly increased the installation's footprint, and this was decided against.

Similar to the Bike Wall quiz, the game dictates a pace (albeit not as fast), and copies a schema from quiz shows. Its disadvantage is that users are not free to generate their own connections, and might lack the time to talk about the objects and questions. In contrast, both the Jurascopes and the microscope table allow visitors to create their own connections, do not dictate a pace (the Jurascopes animations are rather slow), and provide control to the visitor. Both are closely aligned, providing strong visual continuity cues.

This discussion of additional examples at attempts for spatio-contextually embedded systems provided insight into design aspects that strengthen contextual ties between the system and the artefacts it is intended to relate to, or that weakens and breaks these ties. Empirical evidence suggests that highly embedded systems support lively and frequent human indexing activities, whereas with weak or non-distinct ties, indexing

behaviours and deep engagement with the underlying content tend to be rare. The discussions in this chapter have begun to reveal important design considerations and pitfalls that will in the following be distilled into design strategies.

4. STRATEGIES FOR SPATIO-CONTEXTUAL EMBEDDING IN SUPPORT OF INDEXING

A new issue emerging from the studies presented in this article is how to design for indexicality. This means more than just integrating systems into a context; it is about purposely enabling users to make comparisons and references in both directions (between system/visual representation and environment/referenced objects and back). In the cases described, indexes were predominantly implicit, and it was up to users to do the actual indexing, leaving agency to them (cf., [Rogers 2006]) on supporting pro-active people instead of pro-active technology). Our interest is in understanding what features of a technology engender and support people in indexing.

Therefore, we need to understand the design considerations to be taken into account when developing spatio-contextual embedded systems. What if the screen in the Jurascope case study would not be embedded in the floor? What if it faced the other way? What if the skeletons in the animations would not be those from the exhibition floor? These are just some of the aspects that could influence the degree of "embeddedness" and how well indexing is engendered by it. The analysis of embedded interactions from the various case studies in this article has revealed a number of potential strategies, and sharpened our perception for issues that diminish people's ability to index. Systematizing our insights into such strategies provides a pragmatic outcome of our research, which may be useful for interaction designers and museum curators/practitioners.

While far from being able to provide guidelines and rules, the case studies allow us to deduce promising design strategies for the creation of spatio-contextual embedding, and in turn, for support of users' indexing. Moreover, for many areas of interaction design prescriptive rules are too formulaic and do not lend themselves to dealing with design trade-offs. We here thus describe design strategies, or "sensibilities" [Ciolfi 2004; Fitzpatrick 2003; Wright et al. 2008] that focus on what to achieve, rather than to avoid. The strategies are translated into a question format, as this can make conceptual work more accessible for designers (see [Hornecker 2010b]) who dislike the vocabulary of design rules and guidelines, preferring open phrasing.

In the following, we assume a setup where there is an object, or series of real-world objects that a computerized system that users interact with refers to, as was the case in the case studies. Table I gives an overview of the set of strategies. All of these go together to create "contextual embedding." As often in design, if one aspect is lacking, everything may fail. In some cases, two or more design strategies may conflict, or might conflict with another system design goal, requiring a careful consideration of trade-offs. Designers thus need to think on multiple levels.

To start with, there needs to be a *meaningful relation* between the activity that users are asked to do and the objects that the system relates to. The system should invite users to think about and engage with the real artefacts, and enrich these in some way. The car-wall musical game is a counter example, where the game activity is not related, and does not reveal much insight on the cars [Figure 13(a)-(d)]. This game even prevented visitors from looking at the cars, as attention needed to focus on the screen. The two other multiplayer games discussed in the final section adhere to this strategy, since the quiz questions require the user to look at the objects and think about these, resulting in an extended understanding of the exhibited artefacts, as do the other case studies. Beyond these examples, this relation is not restricted to searching information and answering questions, but can include an imaginative, creative engagement as in some of the related work discussed in the background section (cf. [Bidwell and Browning 2010; Halloran et al. 2006; O'Hara and Kindberg 2007; Perry 2012]).

Table I. Strategies for the Creation of Spatio-Contextual Embedding and the Support of Indexing

Strategies and sub-Strategies			Core Question
Meaningful relation of activity with target			Does the activity evoke insights on the objects/representations (on both sides)?
User control			Is there enough opportunity to index, and to communicate?
	Pacing of activity (direct control or slow pace)		Is there enough time to notice or make the connections, and to think about them?
	Repeatability		Can people return to it to deepen their engagement, to compare, and communicate about this or does the system rush users?
Support for discovery			Is there perceptual support to make or discover connections?
	Lines of Sight/Directional Mappings		
		Alignment in time and space	Are the related entities visually aligned with each other in time and/or space so that connections are easy to see and point out?
		Viewpoints	Taking account of sight lines in content design
	Visual salience		Do the important elements stand out, and guide viewer's attention? (reducing cognitive effort for perception)
Openness to interpretation			Is there a larger space of potential user reactions, and for creativity?
Support for Sharing: Visibility and Legibility			Can others notice and follow the references? Is it easy to share these?

Another set of strategies concerns whether people are able to discover, follow and make connections or whether the type of activity and the setup hinder them from doing this. The first set of strategies increases users' opportunity to index, to think about connections, and communicate about it, increasing their engagement with content. Giving users some *control*[8] over the *pace* of the activity, being slow pace and allowing for breaks (as with the magnification lens table and ship conveyor belt), or to allow for *repeats* (as with the Jurascopes) is important to allow for indexing activity. This is because we cannot predict *when* users will do this, how their engagement will play out, and what exactly they will focus on.

The *degree of pacing* effects people's ability to index, make references and go back-and-forth because it determines how much time they have to do so, and whether they feel rushed. Perry [2012] recommends letting visitors interact at their own pace, so they feel in control of their experience. Most of the games we observed violate this principle. Here, we argue that self-controlled pace also supports visitors meaning-making. Fast-paced systems such as the motorcycle quiz show (or the car-wall musical game) may make it difficult for users to understand the relation between objects. More importantly, they do not provide time to reflect, to discuss with others, to align focus with companions, and to investigate further. In contrast, the magnification lens table does not provide any pacing at all, leaving users in full control. Its static nature supports visitors in negotiating and establishing shared focus. The Jurascopes are rather slow-paced, with each animation giving users some time to look back-and-forth,

[8]To note, these are aspects of user control, but not identical with the common Usability guideline of 'user control'.

and to comment on the clip, as evidenced by the lively conversations around the screens. Moreover, once a clip has finished, users are not rushed to the next one, but may take as long as they wish to select the next skeleton for the animation, and can abort this by moving the lever back anytime. A lot of indexing activities were observed at this "navigation stage," before or after a clip had been watched. The ship conveyor belt, while dictating a pace, is very slow paced, leaving time for discussions to emerge.

Imposed pace interferes with an individual's ability to create meaning and also with negotiating alignment of attention with companions, which, as revealed in ethnomethodological studies of visitor interactions [Heath and vom Lehn 2004], often necessitates repeated attempts of explication and verification by the involved participants. Here, participants orient not only to the reference itself, but also to the process of its production, as the concrete timing and alignment of gesture with other aspects of the setting provide crucial information. If the pace of an installation does not enable participants to align their indexing actions in a meaningful way, then it becomes meaningless for observers.

Repeatability is an alternative strategy that gives users control, enabling them to return to an item and increasing the meaningful connections made. When one can repeat an action, then one can compare the outcomes of different actions more systematically, or show something to one's companions and discuss discoveries made. The Jurascopes allow users to repeat the same clip several times, enabling them to focus on details, or to discuss the animation with others. The game-style installations do not provide repeatability, since visitors would have to play through several rounds of questions to restart.

Another set of strategies concerns perceptual *support for discovery* of connections, such as direct lines of sight, spatial and time-based *alignment* (or mapping), and highlighting of elements and structure through *visual salience*.

A successful strategy for spatio-contextual embedding, which supports indexing, evident in several of the case studies, is *alignment*, as well as the consideration of *viewpoints* or vistas (cf., Bitgood's [2013] discussion of how to support visual search through sightlines). These support the perceptual process and enable users to focus on the important elements and the discovery and generation of connections. The careful alignment of the Jurascopes (and the virtual view they offer) with the real skeletons in the same room made it easy for visitors to realize how the technical system and the real artefacts relate, to point back-and-forth between the two, and to use one as index to the other [see Figures 2(b), 6(a) and (b), and 7(a) and (b)]. We saw the same at the magnification lens table. The ship conveyer employs a very simple and direct strategy of visual-spatial and time-wise alignment. When on one occasion, due to a technical glitch, the screen contents did not relate to the ships passing by, visitors were clearly confused, and seemed to spend far less time at the exhibit and talk less about the ships. One of the short examples introduced, the "Wheel of Fortune" quiz, illustrated the care required to ensure alignment and availability of lines of sight when dealing with physical artefacts and settings [see Figure 15(a) and (b)]. In this case, line of sight occluded an exhibit. In the case of the car-wall musical game, alignment only existed in principle because of the sheer scale of the setup.

Besides of alignment, *visual salience* appears a successful strategy to support people in relating back-and-forth, and in making it easy to find the relevant objects. Both reduce the cognitive effort of matching two representations (the digital system and the real objects). According to Kress and Van Leeuwen [2002], salience as an element of composition directs the viewers' attention through placement, size, brightness or tonal contrast, and other factors such as difference in sharpness of the image. Salience is independent of content and information value, and only concerns visual structure; it can highlight or background features of the representation.

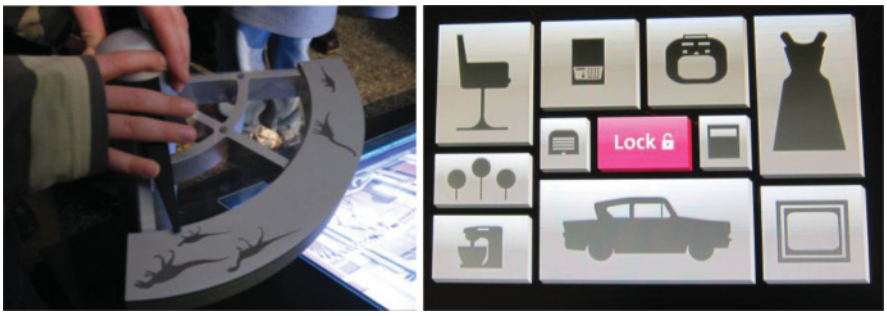

Fig. 16. (a) Visual salience of the dinosaurs on the physical lever for selecting among four dinosaurs (it contains a larger chasing a small dinosaur). (b) Wheels of Fortune player display.

The motorcycle/bike wall quiz [Figure 14(a) and (b)] illustrates that alignment does not always suffice. While the grid on the screen is a rough representation of the show wall, the sheer number of items and their abstract, anonymous shape do not provide clues for the human perceptual system, as neither shape nor arrangement stand out. Yet, despite the enormous number of objects in the Cabinet of Curiosities wall display related to the magnification lens table [Figure 10(a) and (b)], museum visitors did not seem to find it problematic to relate the two. This was because nothing was rushing them, and they could do the activity at their own pace. Moreover, the photographic representation had visual salience, as the objects within the glass cabinet have very different appearance, and the photo on the table even replicates the lighting and spotlights of the cabinet. Similarly, the Jurascope dinosaurs are visually very distinct, so that even the comic-style abstractions on the physical lever are easy to recognize [Figure 16(a)]. The "Wheel of Fortune" screen [Figure 16(b)] also provides visual salience for museum visitors to quickly glance back-and-forth between screen and cabinet. The screen shows the objects distinctive shapes, sizes, and their overall arrangement, which, unlike the motorcycle wall, is not a regular grid.

A further supporting strategy may be *openness to interpretation*, meaning that the system does not close down the space of potential relations, reactions, and indexes that users might generate. The Jurascopes are a prime example here, and the observations reveal a wide range of how visitor groups integrate them into their conversation, verbally enacting and commenting on the storyline, imagining to be in the same space with the dinosaurs, playing with the screen, showing off knowledge, and engaging in educational conversations. The Magnification Lens Table does leave the space of interpretation open, and invites marvelling and wonderment. The ship conveyor belt, while suggesting themes and topics through the content of the screens (e.g., information about the size of the ships, the shipyard they were made in, their route and usage type for passengers, goods, warfare, and so on), leaves it open to visitors which of these snippets of information to react to, and how. In contrast, the specificity of prompts and questions given in quiz shows along with their fast-paced nature, where one question follows the other, result in a reduced space of potential visitor reactions and interpretations. If we adopt the quiz scheme, it might be advisable to give users more time to select choices, and to allow for a pause between revealing the answer to one question and delivering the next. This would then allow people to reconsider the question, and to inspect the objects in more detail.

Bedford [2014] similarly argues for the "need for imagination to be given enough breathing space." Such openness was also a characteristic of the mobile fieldtrip experience from earlier work by the authors in the Chawton House project [Halloran

et al. 2006] where many of the systems prompts invited creativity, allowed for subjective responses and called for close attention to the environment, without requiring a "correct answer."

Inspired by Heath et al. [2002b], we might add a further potential design strategy that focuses on supporting the communicative and social function of indexing: installations need to provide resources for "rendering the actions and activities of others within the space intelligible." This may translate to ensuring that people's indexing behaviours are *visible and legible to others*, so that these, for example, can determine what someone is indexing at and what meaning they confer with this. Given gesture is ephemeral, its visibility at the point of production is central for shared meaning making (albeit not required for individual cognition).

The two versions of the Jurascope here provide a telling contrast. With the telescope version, others can only see the viewer pointing at the exhibition hall, but cannot see the display. This not only makes it harder to ascertain what exactly the viewer is pointing at, it is invisible what it is being connected with. The concrete semantics of the indexing act are thus obscured. This is reflected in the almost complete absence of meaningful discussions at the telescope Jurascopes, when these are ubiquitous at the screen-based Jurascopes. The Ship Conveyor Belt provides similar legibility of indexing actions and fosters sustained conversations. With some of the installations, people's talk makes up for reduced legibility (but this requires having enough time). At the magnification lens table groups sometimes split up, with one member at the glass case containing the original exhibits. If the person at the glass case points at something, this is visible to the person at the table, who can read out the animal's name aloud. While none of the case studies provides obvious examples of reduced legibility, awareness research can inform design for legible bodily action. This concerns, for example, support for sharing access to visual or audio information and design for shared experience [Hornecker et al. 2007; vom Lehn 2007], and performativity of action [Reeves et al. 2005].

4.1. Role of the Design Strategies

The summarised design strategies can support designers in evaluating design ideas and in thinking through concepts and identifying potential weaknesses. To start with, if an installation is to have visitors engage with artefacts, a *meaningful relation* between user activity at the installation and artefact displays is essential. The other strategies then support the activity and uncovering of relations by users. *Openness to interpretation* changes the nature of these relations, and reminds designers of the potential of emotional, imaginative engagement strategies for museum and heritage learning. *User control* and *support for discovery* are both enabling meta-strategies. *Pacing* and *repeatability* can be utilized as alternative strategies to enable user control, e.g., fast pace but short segments that can easily be repeated allow visitors to show each other something, as they can replay what they want to refer to. *Pacing* and *repeatability* along with *visibility of action* appear to be especially important for social interactions and the emergence of group dialogue. *Support for discovery* appears important for both individual and social scenarios of use, given the need for immediate apprehendability of museum interactives and the typically high numbers of first-time users in museums. The less time people have (the faster they are paced) the bigger the need for visual *salience* and good *lines of sight*.

The case studies further indicate that a gamification approach may be harmful (in particular, within a museum and heritage context) if game design ignores the larger context of what the game is about. Fast-paced games tend to only work as standalone activities, as they do not allow time for reflection and for relating the game with the environment. If installations are meant to augment the environment or material exhibits nearby, then people need to be able to shift attention to these, and to control

pace [cf., Perry 2012]. Pace has been largely discussed in the HCI literature around issues of responsiveness to input, and the ability of users to control pace [Kidd et al. 2011]. As the range of examples presented here demonstrates, there is no one optimal pace, and while user control of pace is recommended (a standard usability principle) in some cases it might even be beneficial to dictate a (slow) pace, which forces users to slow down and to anticipate future action.

As the discussion of some of the shorter examples revealed, it may not always be practically possible to adhere to all strategies. The Wheel of Fortune could not be given enough floor space to ensure optimal lines of sight. Designers might also decide to favour a specific game idea that requires fast speed, if criteria outside of the scope of this article are rated higher. But the strategies listed here will provide awareness that a fast game will be unlikely to engender discussion about the artefacts. Talking to museum curators, it is clear that there is a multitude of such considerations, and numerous practical and financial constraints. The strategies listed here may in the future assist in making more informed decisions in weighing between design alternatives and trade-offs.

5. DISCUSSION AND CONCLUSION

In this article, the role of referential back-and-forth indexing in human sense-making activities has been illustrated in the context of museum visiting. In the first set of case studies, human practices of *indexing* were highlighted and analysed—acts of referring back-and-forth between the here and the there, drawing connections between different entities (or representations). This type of indexing is an essential part of sense making in relating between two (or more) spatially distributed entities or representations and quite literally drawing connections between them (in both directions). It uses the mechanisms of "traditional" indexical acts as discussed in gesture and conversation studies (pointing or verbally referring to "there" and "that") but does so in the service of a meaning-making activity that creates new meaning from an assemblage of entities. In this, all entities gain meaning from the constellation they are in and that people interpret. Indexing can be done as part of individual sense making or in social interaction. From a viewpoint of embodied and situated cognition, it is an embodied interaction, being an embodied relationship with a situation or environment.

This article has illustrated how indexing practices support human sense-making and engage people with their surroundings. It further investigated what makes out systems that support indexing (as a complex form of sense-making and reciprocal relating between different representations/ entities) and provided some insights into design strategies. The term *spatio-contextual embeddedness* was proposed to describe systems that follow these strategies, and thus, support indexing. We thereby re-appropriate the term "embedding," which has come to be utilised primarily in a technical context. In this sense, interaction is embedded in socio-cultural and physical contexts.

Two core values for design underpin this article: (1) the primacy of the real object and environment and (2) support of human agency in active indexing.

As a design notion, spatio-contextual embedding seeks to retain the primacy of the original environment/objects. It creates visible relationships between a system and the environment it is integrated in, and thereby, augments the setting. This addresses a vital concern for many museums and heritage sites that aim for museum installations that augment and enrich original museum artefacts and settings without diverting attention from them. Spatio-contextual embedding takes its strength from how embodied activity is always embedded within an environment [Luff et al. 2013], using this embeddedness to add meaning, or rather to have the user discover and create meaning. The case studies illustrated that spatio-contextual embedding can be implemented independent of technology, and may even be realized via rather traditional interactive screens that relate to exhibits in full view.

Moreover, as the case studies demonstrate, spatio-contextual embedding supports indexing practices, in which users actively (and mindfully) engage with their environment. Supporting human agency leaves the responsibility for creating meaning with users, inviting them to do so, and gives space to explore and wonder. This aligns with visitor research that stresses that exhibition design should support discovery, sense/meaning-making and imagination [Bedford 2014; Ciolfi and Bannon 2002; Diamantopoulou 2013; Humphrey et al. 2005; Perry 2012] and with contemporary understandings of museum learning as dialogic, constructivist, and contextual [Falk and Dierking 2000].

The analysis in this article is inspired by perspectives on "indexing" practices from Ethnography, Communication Studies, and Distributed Cognition, the former focusing on the analysis of human coordination practices, where deixis and indexical expression support implicit communication, and the latter contributing the notion of "indexing for yourself," such as pointing as a memory aid for individual cognition. In the literature, so far there has been little explicit emphasis of the role of this type of back-and-forth referential action, even though it has been illustrated in occasional examples (e.g., [Goodwin 2003; Heath and vom Lehn 2004]). Pointing and indexing is something we do spontaneously when we communicate, explain things to each other, and engage with the world around us. It is built into our language [Clark 2003; Garfinkel 1967] and is a resource we draw upon in sense-making (both actively in words and gestures and also when observing others who index). Our analysis has highlighted how different decisions in the design of museum installations impact on the ability of visitors to engage in such indexing in their meaning-making, both when on their own, and in social interactions.

For example, the temporal organisation of gestural activity is choreographed within simultaneous "semiotic fields" of talk and environment [Goodwin 2000], as a co-occurring representation from gesture, speech, and environment [Hutchins and Palen 1993; Jones and LeBaron 2002]. The alignment of attention when shifting between two different referents constitutes a complex accomplishment [Goodwin 2003]. In interactions between visitors, we frequently observed repeated attempts to generate this alignment and recipient designs of gesture [Hindmarsh and Heath 2000]. The fleeting nature of gesture renders it vulnerable to distraction, but also enables it to be utilized as a resource, continuously adjusting to circumstance and its recipients' shifting focus. Awareness of the complexity of these human coordination mechanisms informed the analysis of data from the case studies and the reflection on what design strategies support these behaviours. For instance, from this theoretically informed understanding it becomes clear that fast-paced installations interfere with the negotiation of alignment (which often requires multiple attempts of establishing "I see you seeing me" glances and gestural "dances") and with recipient design of gesture. Sight lines and clear alignments further ease the recipient design of indexing gestures.

The Distributed Cognition perspective has guided analysis of case study data to take note of instances where indexing is not part of social interactions, but occurs in solitary situations. Here, participants index to a lesser extent using gestures, but also index by shifting attention back-and-forth, making the same kinds of connections as in social settings. Pointing sometimes serves as epistemic action to guide attention and mark an object while shifting attention elsewhere. This "indexing for oneself" also needs to be supported by system design. The distributed cognition theory provides us with further appreciation that participants need adequate time to create their gesture as an externalisation of thought, perceive their gesture and reflect on it, directing their attention between both points of interest.

Our analysis indicates that individual indexing is supported by the same mechanisms as "social indexing," but that the latter relies on visibility of action, which the former

does not require. We have seen this in the Jurascope case study, where the telescope version of the installation supported individuals in indexing for their own benefit, but did not support conversation.

Beyond the conceptual contribution of highlighting the activity of indexing, this article also has a pragmatic aim. Its practical contribution lies in investigating through analysis of real-world examples how indexing actions are engendered and triggered, what makes out systems that support indexing, and condensing this into a set of design strategies. This article emphasised indexing as the active production of indexes rather than that of following given indices and pointers. Too often, technology aims to direct and steer us, and prescribes meaning. An alternative, in the tradition of technology that supports human agency and designs for pro-active people [Rogers 2006], is to design technical systems in a way that supports the human activity of indexing as a part of sense-making [Suchman 2007] and mindful engagement with our environment. A new issue emerging from the analysis of case studies thus is *how to design for indexicality*. This means purposely enabling and empowering users to make comparisons and draw meaningful connections of their own choosing. It means leaving agency to users, with technology being merely a "resource for action" [Fernaeus et al. 2008]. This fits into the discourse in museum literature on supporting minds-on and hearts-on learning [Adams et al 2004], where visitors are not just consumers of information, but engage in active meaning-making. The support of indexing thus is a design approach for visitors' agency (cf., [Diamantopoulou et al. 2012]). How to support designers in designing for indexicality, therefore, is an important issue for further research (see outlook and future work).

Our analysis of spatio-contextual embedding furthermore is part of a *larger discussion in HCI around locality, place-ness,* designing for place/location, physical context, and the experience of place [Bidwell and Browning 2010; Ciolfi 2004; Jones 2011; Messeter 2009; O'Hara and Kindberg 2007; Schaefer et al. 2010]. There has been increased interest in HCI in how interaction is embedded in a social, cultural, and architectural-physical context, where the context influences people's interactions, and how to design for this embedding [Luff et al. 2013]. Spatio-contextually embedded design is related to the notion of place-specific computing [Messeter 2009], where functionality and information are "inherently grounded in" the social and cultural practices and material conditions of a place. Design for indexing similarly emphasizes designing for the "here and now" to enhance place, but focuses on connecting users with the environment, as other attempts [O'Hara and Kindberg 2007; Schaefer et al. 2010] do via location-based content delivery.

Other work has explored the notion of *embedded mixed realities*. Schnädelbach et al. [2010] focus on the overlaying of mixed reality spaces where conduct can move seamlessly between real and virtual interaction spaces. These are embedded via an overlap of co-existing connected worlds, for example, allowing remote participation. "Embedding" takes a different form and has a different purpose than in the current article, but also relies on careful placing and visibility.

In investigating how to support engagement with the environment or with key objects via technological augmentation and careful embedding of technology within a hybrid ecology, our work is related to other attempts at *orchestrating the user experience on a larger temporal and spatial frame*, in particular, to Benford's trajectory framework [Benford et al. 2009] and Fraser et al.'s [2003] notion of an assembly of displays or devices, which support a coherent overall experience. It complements these with *local level strategies*, focusing on individual installations and how to maximise their impact.

Like our own work, the aim of Fraser et al.'s [2003] assemblies is to enable visitors to draw connections between different elements of an exhibition (and historical events), where displays are meaningfully embedded within the visiting experience. But assemblies denote a collection of installations at the level of an entire exhibition

or heritage visit. The assembly strategies create a unifying activity that holds the visit together, where each display supports parts of the activity. In contrast, our discussion of "indexing" and how to support it emphasises how to extend the engagement with a single installation or display-artefact assemblage, albeit some of our prior work puts local engagements in the context of an overarching activity (the Chawton House project mentioned briefly).

Benford's trajectory framework [Benford et al. 2009] also focuses on a larger temporal scale, orchestrating the user experience (journey) at a global level, similar to a theatre experience where the audience is led from scene to scene, with narrative elements. It emphasizes transitions and connections between parts of the space and activities, in particular, in the context of hybrid spaces that connect physical and virtual environments. This sounds similar to our work, but works at a more global and narrative level for entire experiences that are carefully orchestrated, having "distinctive temporal structure," while building on narrative and dramaturgy. While issues of pacing and rhythm are mentioned, this is primarily on a global level, e.g., pacing refers to enabling participants to disperse and re-engage with each other. The trajectories work emphasizes the design of ideal paths (canonical trajectories), focusing on how to draw people in and how to provide smooth transitions (between different episodes or between real and virtual worlds). Viewpoints and vistas here play a role in drawing people in or enticing them to the next stage. In these complex experiences, users navigate a space of interactions and meanings, and orchestration directs them through this to generate an optimal experience. With our notion of "indexing support," the designer does not take on the role of an invisible conductor or script writer, but gives more space to human agency, supporting sense making in local moments. Nevertheless, some of the insights presented in the current article relate to the trajectories work and may enhance its principles. For example, Fosh et al.'s [2013] discussion of a case study of trajectory design notes how visitor activities triggered by a guide system to a sculpture garden need to be meaningful in relation to the object (our first strategy) and may include imaginative activities and some ambiguity, reminding of our strategy "Openness to interpretation." The strategies emerging from our case study discussion provide more detail on *how exactly* instructions and contents can support the "approach" and "engage" phase of local trajectories so as to foster active sense making and engagement.

A few other frameworks also focus on the social interactions around installations, in particular Reeve's spectator experience framework [Reeves et al. 2005]. It investigates a different section of the design space of public interfaces, focusing on visibility and legibility of actions as well as system reactions and the effects of hiding or emphasizing either. If actions are to be understandable for an audience, they need to be visible and potentially "enhanced." Actions comprise interface manipulations and other actions "around" the interface that may serve to emphasize the activity (or, like a magician, to distract), to communicate, or may be part of the users' mental preparations. Hiding actions or effects creates a different experience, as in magic or private activity. Reeves discusses an example for a private experience (hidden effects), a telescope-like device, which is very similar to the Jurascope-telescope and the solitary, private user experience it provides. We can interpret collaborative indexing actions as performative. Our strategy of visible and legible action, thus, relates to one of the quadrants of Reeve's analysis of hidden/emphasized actions/effects. But Reeve's framework does not discuss the relation of installations to the outside world or people's attempts at drawing connections between one interface and the surrounding environment, or at communicating these connections to their companions.

In distinction to these other frameworks that focus on long-term trajectory orchestration and real-virtual mixed realities, the focus of this article has been on understanding how to design for indexing. For this, we first needed to develop a clear and rich

understanding of what we mean with "indexing" actions, based on empirical case studies, and an analysis of how the installations from these case studies are embedded in their environment. This leads to the notion of "spatio-contextual embedding," which describes how a system relates to its environment so that their juxtaposition creates added meaning, which people then discover when indexing. From this understanding, a number of design strategies have been distilled, which may be useful for system designers who aim to support users' active indexing. It is hoped that the work presented here is both of theoretical interest for a better understanding of human sense making and of practical relevance for system designers, in particular, within the domain of museum installations.

5.1. Limitations of this Work and Future Research Questions

To conclude, a brief outlook addresses limitations of the work presented and sketches leads for future research. The analysis in this article has been based solely on examples from a museum and heritage context. This is an area where digital media are often meant to augment and enrich existing environments and objects, and where their spatio-contextual embedding is obviously important. While so far we do not have examples from other domains, it can be argued that the analysis extends to other domains, for example, education and learning, where physical objects and models are often involved, as well as other areas where an external representation augments a physical object. For example, for medical experts in surgical operating theatres, the ability to interact with CT and MRI scans on displays is crucial [O'Hara et al. 2012]. These screens are used for common reference, diagnosis, planning of procedures, and to navigate surgical equipment during analysis of images. Pointing at and relating them to patient's bodies resembles the notion of "indexing" discussed in this article. Whereas casual or novice settings (such as museums) require users to discover relations, for this expert scenario strategies such as visual salience and clear alignment will be less vital. Of higher relevance will be pacing, repeatability, and the support for sharing through visibility and legibility of actions. Visual alignment may ease communication. Future work is needed to explore the utility of the understanding of spatio-contextual embedding and indexing support laid out in this article within other application contexts and to extend and deepen the analysis of potential design strategies and their relation to the requirements of different use contexts.

The analysis of indexing can very likely be extended to mobile scenarios, as evidenced by the Chawton House project [Halloran et al. 2006] and other projects using mobile technologies to enhance people's engagement with their environment [Bidwell and Browning 2010; O'Hara and Kindberg 2007; Schaefer et al. 2010]. Here, mobile experiences are carefully crafted to connect different elements of the surroundings and mobile contents, and to direct users' attention towards the surroundings. Similarly to the installations discussed in this article, mobile content may only gain its full value when experienced in the right location and when interacting with the environment.

Another potential limitation of this article is that it focused primarily on situations where digital representation and physical entity are distributed in space, with a visual-spatial distance. Does the notion of indexing also apply to representations with a temporal gap, or based on non-visual modalities? How can the design strategies be translated for this? Further, research on perception might provide important indicators for cognitive complexity that could enhance our understanding of how to design for indexing.

An issue that the analysis has raised is how to support designers in pursuing the design strategies for spatio-contextually embedded installations. This may require dedicated design and prototyping methods and tools. In our prior research, the role of in-situ authoring became apparent in the Chawton House project [Weal et al. 2006].

Intriguingly, the design process of spatio-contextually embedded activities benefitted from contextual embedding in the form of in-situ authoring. As noted by Bidwell and Browning [2010], the concrete experience of a place is important when designing content for it. Not only do the surroundings inspire and trigger ideas, but authors can also better imagine and assess what it will be like for the recipient. Similarly, the design of new installations may benefit from ideation and prototyping in-situ, or from a direct experience of how the design will integrate into and interact with the context. Traditional design practice offers little tools to design for and test spatial embedding, visual alignment, and creation of views at early product stages. In some cases, 1:1 models can be built, but this is not always feasible, as was the case with the car-wall display and related game. Some research has begun to investigate the use of projection and simulation with physical small-scale models [Jacucci et al. 2005; Nakanishi 2012; Singh et al. 2006] to better anticipate the user experience and improve overall consistency of design. But many aspects need to be experienced in 1:1, such as the scale of the car wall and might benefit from new technologies enabling the direct experience of 3D exploration. This is an area for further research.

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REFERENCES

Marianna Adams, Jessica Luke, and Theano Moussouri. 2004. Interactivity: Moving beyond terminology. *Curator* 74, 2, 155–170.

Sue Allen. 2004. Designs for learning: Studying science museum exhibits that do more than entertain. *Sci. Educ.* 88, S1, S17–S33.

Martha W. Alibali, Rececca Boncoddo, and Autumn B. Hostetter. 2014. Gesture in reasoning. An embodiment perspective. In. *The Routledge Handbook of Embodied Cognition*, L. Shapiro (Ed.). Ch. 15. Routledge. 150–159

Liam Bannon, Steven Benford, John Bowers, and Christian Heath. 2005. Hybrid design creates innovative museum experiences. *Commun. ACM* 48, 3, 62–65.

Yehoshua Bar-Hillel. 1954. Indexical expressions. *Mind* 63, 251, 359–379.

Katja Battarbee. 2003. Defining co-experience. In *Proceedings of DPPI 2003*, ACM, New York, 109–113.

Leslie Bedford. 2014. The Art of Museum Exhibitions: How Story and Imagination Create Aesthetic Experiences. Left Coast Press, Walnut Creek, CA.

Steve Benford, Gabriella Giannachi, Boriana Koleva, and Tom Rodden. 2009. From interaction to trajectories. In *Proceedings of CHI 2009*. ACM, NY.

Nicola Bidwell and D. Browning. 2010. Pursuing genius loci: Interaction design and natural places. *Personal Ubiquitous Comput*. 14, 1, 15–30.

Stephen Bitgood. 2013. *Attention and Value. Keys to Understanding Museum Visitors.* Left Coast Press, Walnut Creek, CA.

Jeanette Blomberg, Jean Giacomi, Andrea Mosher, and Pat Swenton-Wall. 1993. Ethnographic field methods and their relation to design. In *Participatory Design*, D. Schuler and A. Namioka (Eds.). Lawrence Erlbaum, Mahwah, NJ, 123–155.

Richard A. Bolt. 1980. "Put-that-there": Voice and gesture at the graphics interface. *SIGGRAPH Comput. Graph.* 14, 3 (Jul. 1980), 262–270.

James Bradburne. 2002. Museums and their languages—is interactivity different for fine art as opposed to design? In *Proceedings of Interactive Learning in Museums of Art.* V&A Museum, London.

Massimiliano L. Cappuccio, Mingyuan Chu, and Sotaro Kita. 2013. Pointing as an Instrumental Gesture: Gaze Representation Through Indication. *Humana. Mente J. Philosophical Stud.* 24, 125–150.

Luigina Ciolfi. 2004. *Situation 'Place' in Interaction Design: Enhancing the User Experience in Interactive Environments*. Ph.D. thesis, University of Limerick, Ireland.

Luigina Ciolfi. 2013. The collaborative work of heritage: Open challenges for CSCW. In *Proceedings of E-CSCW 2013.* Springer, London, 83–101.

Luigina Ciolfi and Liam Bannon. 2002. *Learning from Museum Visits: Shaping Design Sensitivities*. Technical Report IDC-University of Limerick, Ireland.

Luigina Ciolfi and Mark McLoughlin. 2011. Physical keys to digital memories: Reflecting on the role of tangible artefacts in "Reminisce." In *Proceedings of Museums and the Web 2011*. Archimuse.

Andy Clark and Being There. 1997. *Putting Brain, Body, and World Together Again*. MIT Press, Cambridge, London.

Herbert Clark. 2003. Pointing and Placing. In *Pointing: Where Language, Culture and Cognition Meet*, S. Kita (Ed.). Lawrence Erlbaum, Mahwah, NJ, 243–268.

Loraine Clarke and Eva Hornecker. 2013. Experience, engagement and social interaction at a steam locomotive multimodal interactive museum exhibit. In *ACM CHI'13 Extended Abstracts*. ACM, New York, 613–618.

Loraine Clarke. 2013. *An interview with the Riverside Transport Museum in Glasgow on their Design Approach to Interactive Installations*. (Oct. 2013). Retrieved April 23, 2015 from http://mesch-project.eu/an-interview-with-the-riverside-transport-museum-in-glasgow-on-their-design-approach-to-interactive-installations/.

Clarisse de Souza. 2005. *The Semiotic Engineering of Human-Computer Interaction*. MIT Press, Cambridge, London.

Sophia Diamantopoulou, Eva Insulander, Gunther Kress, and Fredrik Lindstrand. 2013. Making meaning in an exhibition: Technologies, agency and (re-)design. In *Proceedings of the Tranformative Museum.* Roskilde University. Danish Research Center on Education and Advanced Media Materials. University of Southern Denmark. Odense. 110–127.

Zahada D. Doering. 1999. Strangers, Guests, or Clients? Visitor Experiences in Museums. *CURATOR* 42, 2 (Apr. 1999), 74–87.

Paul Dourish. 2001. *Where the Action Is. The Foundations of Embodied Interaction*. MIT Press, Cambridge, London.

Sandra Dudley (Ed.) 2010. *Museum Materialities: Objects, Engagements, Interpretations*. Routledge.

Maria Economou. 2010. The evaluation of museum multimedia applications. In *Museums in a Digital Age*, Ross Parry (Ed.). Readers in Museum Studies, 391–405.

Kerstin Ellenbogen, Jessica Luke, and Lynn Dierking. 2004. Family learning research in museums: An emerging disciplinary matrix? *Sci. Educ.* 88, 1, 48–58.

John H. Falk and Lynn Dierking. 2000. *Learning from Museums: Visitor Experiences and the Making of Meaning.* AltaMira Press.

John H. Falk and Lynn Dierking. 2012. *Museum Experience Revisited*. Left Coast Press, Walnut Creek, CA.

Ylva Fernaeus, Jakob Tholander, and Martin Jonsson. 2008. Towards a new set of ideals: Consequences of the practice turn in tangible interaction. In *Proceedings of Tangible and Embedded Interaction TEI 2008*. ACM, New York, 223–230.

Geraldine Fitzpatrick. 2003. *The Locales Framework*. Kluwer, Dordrecht.

Mike Fraser, Dana Stanton, Kher Hui Ng, Steve Benford, Claire O'Malley, John Bowers, Gustav Taxén, Kieran Ferris, and Jon Hindmarsh. 2003. Assembling history: Achieving coherent experiences with diverse technologies. In *Proceedings of ECSCW'03*. Kluwer, Dordrecht, 179–198.

Lesley Fosh, Steve Benford, Stuart Reeves, Boriana Koleva, and Patrick Brundell. 2013. 'See Me, Feel Me, Touch Me, Hear Me': Trajectories and Interpretation in a Sculpture Garden. In *Proceedings of CHI'13*. ACM, New York.

Ben Gammon and Alexandra Burch. 2008. Designing Digital Mobile Experiences. In *Digital Technologies and the Museum Experience*, Loic Tallon and Kevin Walker (Eds.). Altamira Press, 35–60.

Harold Garfinkel. 1967. *Studies in Ethnomethodology*. Prentice-Hall, Englewood Cliffs, NJ.

S. Goldin-Meadow, S. W. Cook, and Z. A. Mitchell. 2009. Gesturing gives children new ideas about math. *Psychological Sci.* 20, 3, 267–272.

Charles Goodwin. 2000. Action and embodiment within situated human interaction. *J. Pragmatics* 32, 1489–1522.

Charles Goodwin. 2003. Pointing as Situated Practice. In *Pointing: Where Language, Culture and Cognition Meet*, S. Kita (Ed.). Lawrence Erlbaum, Mahwah, NJ, 217–241.

Joshua P. Gutwill and Sue Allen. 2010. *Group Inquiry at Science Museum Exhibits. Getting Visitors to Ask Juicy Questions.* Exploratorium/Left Coast Press. Walnut Creek, CA.

Carl Gutwin and Saul Greenberg. 2002. A descriptive framework of workspace awareness for real-time groupware. *J. Comput. Support. Cooperative Work* 11, 3, 411–446.

John Halloran, Eva Hornecker, Geraldine Fitzpatrick, Mark Weal, David Millard, Danius Michaelides, Don Cruikshank, and David De Roure. 2006. The literacy fieldtrip: Using ubicomp to support children's creative writing. In *Proceedings of IDC'06*. ACM, New York, 17–24.

John Haviland. 2000. Pointing, gesture spaces and mental maps. In *Language and Gesture*, David McNeill (Ed.). Cambridge University Press, Cambridge, 13–46.

Christian Heath, Jon Hindmarsh, and Paul Luff. 2010. *Video in Qualitative Research*. Sage.

Christian Heath and Paul Luff. 2000. *Technology in Action*. Cambridge University Press, Cambridge.

Christian Heath, Paul Luff, Dirk Vom Lehn, and Jon Hindmarsh. 2002a. Crafting participation: Designing ecologies, configuring experience. *Vis. Commun.* 1, 1, 9–33.

Christian Heath, Svensson M. Sanchez, Jon Hindmarsh, Paul Luff, and Dirk vom Lehn. 2002b. Configuring Awareness. *J. Comput. Support. Cooperative Work* 11, 317–347.

Christian Heath and Dirk vom Lehn. 2002. Misconstruing interactivity. In *Proceedings of Interactive Learning in Museums of Art.* V&A Museum, London.

Christian Heath and Dirk vom Lehn. 2004. Configuring Reception: (Dis-)Regarding the 'Spectator' in Museums and Galleries. *Theory, Culture Soc.* 21, 6, 43–65.

Christian Heath, Dirk vom Lehn, and J. Osborne. 2005. Interaction and interactives: Collaboration and participation with computer-based exhibits. *Public Underst. Sci.* 14, 1, 91–101.

Jon Hindmarsh and Christian Heath. 2000. Embodied reference: A study of deixis in workplace interaction. *J. Pragmatics* 32, 1855–1878.

James D. Hollan, Edwin Hutchins, and David Kirsh. 2000. Distributed cognition: A new foundation for human-computer interaction research. *ACM Trans. Comput.-Hum. Interact.* 7, 2, 174–196.

Eva Hornecker. 2008. "I don't understand it either, but it is cool" Visitor Interactions with a Multi-Touch Table in a Museum. In *Proceedings of IEEE Tabletop'08*. IEEE, 121–128.

Eva Hornecker. 2010a. Interactions around a contextually embedded system. In *Proceedings of TEI'10*. ACM, NY, 169–176.

Eva Hornecker. 2010b. Creative idea exploration within the structure of a guiding framework: The card brainstorming game. In *Proceedings of TEI'10*. ACM, NY, 101–108.

Eva Hornecker. 2011. Let's get physical: The role of physicality in tangible and embodied interactions. *ACM Interact. Mag.* 18, 2 (Mar./Apr. 2011), 19–23.

Eva Hornecker and Jacob Buur. 2006. Getting a grip on tangible interaction: A framework on physical space and social interaction. In *Proceedings of CHI'06*. ACM, NY, 437–446.

Eva Hornecker and Matthias Stifter. 2006. Learning from interactive museum installations about interaction design for public settings. In *Proceedings of OzCHI 2006*. ACM, New York, 135–142.

Eva Hornecker, Paul Marshall, and Yvonne Rogers. 2007. Entry and access—how shareability comes about. In *Proceedings of DPPI'07 (Designing Pleasurable Products and Interfaces)*. ACM, NY, 328–342.

Thomas Humphrey, Joshua Gutwill, and Exploratorium APE Team. 2005. *Fostering Active Prolonged Engagement. The Art of Creating APE Exhibits.* Exploratorium/Left Coast Press, Walnut Creek, CA.

Edwin Hutchins and Leysia Palen. 1993. Constructing meaning from space, gesture, and speech. In *Discourse, Tools, and Reasoning—Essays on Situated Cognition*, L. B. Resnick, R. Säljö, C. Pontecorvo, and B. Burge (Eds.). Series F: Computer and System Sciences, Vol. 160, NATO ASI Series, 23–40.

Edwin Hutchins. 1995. *Cognition in the Wild*. MIT Press, Cambridge, London.

Giulio Jacucci, Antti Oulasvirta, Antti Salovaara, Thomas Psik, and Ina Wagner. 2005. Augmented reality painting and collage: Evaluating tangible interaction in a field study. In *Proceedings of INTERACT'05.* Springer, Berlin, 43–56.

Stanley Jones and Curtis D. LeBaron. 2002. Research on the Relationship between Verbal and Non-verbal Communication: Emerging Integrations. *J. Commun.* 52, 3, 499–521.

Matt Jones. 2011. Journeying toward extravagant, expressive, place-based computing. *ACM Interact. Mag.* 18, 1, 26–31.

Brigitte Jordan and Austin Henderson. 1995. Interaction analysis: Foundations and practice. *J. Learn. Sci.* 4, 1, 39–103.

Lynda Kelly, Gillian Savage, Janette Griffin, and Susan Tonkin. 2004. *Knowledge Quest: Australian Families visit Museums.* Australian Museum, Sydney.

Adam Kendon. 1996. An agenda for gesture studies. *Semiotic Rev. Books* 7, 3, 7–12.

Adam Kendon. 2004. *Gesture: Visible Action as Utterance*. Cambridge University Press, Cambridge.

Jenny Kidd, Irida Ntalla, and William Lyons. 2011. Multi-touch interfaces in museum spaces: Reporting preliminary findings on the nature of interaction. In *Proceedings of "Re-Thinking Technology in Museums*. University of Limerick, Ireland.

David Kirsh. 1995a. Complementary strategies: Why we use our hands when we think. In *Proceedings of 17th Annual Conference of the Cognitive Science Society*. Lawrence Erlbaum, 212–217.

David Kirsh. 1995b. The Intelligent Use of Space. *AIJ* 73, 1–2, 31–68.

David Kirsh. 2010. Thinking with external representations. *AI Soc.* 25, 441–454.

David Kirsh. 2001. The Context of Work. *Hum.-Comput. Interact.* 16, 305–322.

David Kirsh and P. Maglio. 1994. On distinguishing epistemic from pragmatic actions. *Cognitive Sci.* 18, 4, 513–549.

Jasper Kjeldskov and Jenny Paay. 2006. Indexical interaction design for context-aware mobile computer systems. In *Proceedings of OzCHI'06*. ACM, New York, 71–78.

Hubert Knoblauch. 2005. Focused ethnography. *Forum Qualitative Sozialforschung/Forum: Qualitative Social Research,* [S.l.], 6, 3. (Sep. 2005). Retrieved October 9, 2015 from http://www.qualitative-research.net/index.php/fqs/article/view/20/43.

Gunther Kress and Theo Van Leeuwen. 1996. *Reading Images: The Grammar of Visual Design*. Routledge.

Curtis LeBaron, Jennifer Mandelbaum, and Phillip J. Glenn. 2002. An overview of language and social interaction research. In *Studies in Language and Social Interaction*, P. Glenn, C. LeBaron, and J. Mandelbaum (Eds.), Lawrence Erlbaum, Mahwah, NJ, 1–39.

Paul Luff, M. Jirotka, Naomi Yamashita, H. Kuzuoka, Christian Heath, and Grace Eden. 2013. Embedded interaction: The accomplishment of actions in everyday and video-mediated environments. *ACM Trans. Comput.-Hum. Interact.* 20, 1, Article 6.

Mark Macleod. 2013. The right place for interactivity. *Museums Herit. Mag.*, summer 2013, 42–43.

D. Martin. 2000. Audio guides. *Museum Pract.* 5, 1, 71–81.

Laura Maye, Fiona McDermott, Luigina Ciolfi, and Gabriela Avram. 2014. Interactive exhibitions design: What can we learn from cultural heritage professionals? In *Proceedings of NordiCHI'14*. ACM, New York, 598–607.

David McNeill (Ed.). 2000. *Language and Gesture*. Cambridge University Press, Cambridge.

David McNeill. 2005. *Gesture & Thought*. University of Chicago Press, Chicago.

Maurice Merleau-Ponty. 1962. *The Phenomenology of Perception*. Routledge & Kegan, London.

Jörn Messeter. 2009. Place-specific computing: A place-centric perspective for digital designs. *Int. J. Design* 3, 1, 29–41.

Yasuto Nakanishi. 2012. Virtual prototyping using miniature model and visualization for interactive public displays. In *Proceedings of DIS'12*. ACM, New York, 458–467.

Kenton O'Hara and Tim Kindberg. 2007. Understanding user engagement with barcoded signs in the 'Coast' location-based experience. *J. Locat. Based Services* 1, 4, 256–273.

Kenton O'Hara, Richard Harper, Helena Mentis, Abigail Sellen, and Alex Taylor. 2013. On the naturalness of touchless: Putting the 'interaction' back into NUI. *ACM Trans. Comput.-Hum. Interact.* 20, 1 (Apr. 2013), Article 5, 25 pages.

Jenny Paay, Jesper Kjedlskov, et al. 2008. Location-based storytelling in the Urban Environment. In *Proceedings of OzCHI'08*. ACM, New York, 122–129.

Charles Sanders Peirce. 1931–1958 *Collected Writings* (8 Vols.). Charles Hartshorne, Paul Weiss, and Arthur W Burks (Eds.). Harvard University Press, Cambridge, MA.

Andrew J. Pekarik, James Schreiber, Nadine Hanemann, Kelly Richmond, and Barbara Mogel. 2014. IPOP: A Theory of Experience Preference. *Curator* 57, 1 (Jan. 2014), 5–27.

Deborah L. Perry. 2012. *What makes Learning Fun? Principles for the Design of Intrinsically Motivating Museum Exhibits.* Altamira Press.

Leia Pujol-Tost. 2011. Integrating ICT in exhibitions. *Museum Manage. Curatorship* 26, 1, 63–79.

Matti J. Rantanen. 2010. Indexicality of language and the art of creating treasures. In *Proceedings of CHI'10*. ACM, New York, 301–304.

Stuart Reeves, Steve Benford, Claire O'Malley, and Mike Fraser. 2005. Designing the spectator experience. In *Proceedings of CHI'05*. ACM, New York, 741–750.

Toni Robertson. 2000. The public availability of actions and artefacts. *J. Comput. Support. Cooperative Work* 11, 3–4, 299–316.

Yvonne Rogers. 2006. Moving on from Weiser's vision of calm computing: Engaging Ubicomp experiences. In *Proceedings of UbiComp'06*. Springer, Berlin, 404–421.

Camellia Sanford, Karen Knutson, and Kevin Crowley. 2007. "We always spend time together on sundays": How grandparents and their grandchildren think about and use informal learning spaces. *Visitor Stud.* 10, 2, 136–151.

Mike Scaife and Yvonne Rogers. 1996. External cognition: How do graphical representations work? *Int. J.Hum.-Comput. Stud.* 45, 2, 185–213.

Matthew Schaefer, Deborah Tatar, and Steve Harrison. 2010. Can CSCW Technologies Help Us Re-construct Places? In *Proceedings of CSCW'2010.* ACM, New York, 567–576.

Schmidt Kjeld. 2002. The problem with "Awareness." *J. Comput. Support. Cooperative Work* 11, 3–4, 285–198.

Holger Schnädelbach, Areti Galani, and Martin Flintham. 2010. Embedded mixed reality environments. In *The Engineering of Mixed Reality Systems*, E. Dubois et al. (Eds.). HCI Series, Springer-Verlag, London, 57–79.

Marjorie Schwarzer. 2001. Art & Gadgetry—The Future of the Museum Visit. *Museum News*. (Jul./Aug. 2001). American Association of Museums.

Pushpendra Singh, Hai Nam Ha, Zhiwen Kuang, Patrick Olivier, Christian Kray, Phil Blythe, and Phil James. 2006. Immersive video as a rapid prototyping and evaluation tool for mobile and ambient applications. In *Proceedings of MobileHCI'06*. ACM, New York, 264–264.

Iris Soute, Panos Markopoulos, and Remco Magielse. 2010. Head Up Games: Combining the best of both worlds by merging traditional and digital play. *Personal Ubiquitous Comput.* 14, 5, 435–444.

Rolf Steier. 2014. Posing the question: Visitor posing as embodied interpretation in an art museum. *Mind, Culture Activity* 21, 148–170.

Jürgen Streeck. 2009. Gesturecraft. The manufacture of meaning. *Gesture Studies 2 Series*. John Benjamin Publishing Company. 235.

Lucy Suchman. 2007. *Human-Machine Reconfigurations*. Cambridge University Press, New York.

Dirk vom Lehn, Jon Hindmarsh, Paul Luff, and Christian Heath. 2007. Engaging Constable: Revealing art with new technology. In *Proceedings of CHI 2007*. ACM, New York, 1485–149.

Dirk vom Lehn and Christian Heath. 2003. Displacing the object: Mobile technology and interpretive resources. In *ICHIM—International Cultural Heritage Informatics Meeting*.

Mark Weal, Eva Hornecker, Don Cruickshank, Danius T. Michaelides, David E. Millard, John Halloran, David C. De Roure, and Geraldine Fitzpatrick. Requirements for In-Situ Authoring of Location Based Experiences. In *Proceedings of Mobile HCI 2006*. ACM, New York, 121–128.

Andrea Whitcomb. 2006. Interactivity: Thinking beyond. In *Companion to Museum Studies*, Sharon Macdonald (Ed.): Blackwell Publishing, Oxford. 333–361.

Peter Wright, Jayne Wallace, and John McCarthy. 2008. Aesthetics and experience-centered design. *ACM Trans. Comput.-Hum. Interact.* 15, 4 (Dec. 2008), Article 18.

Keiichi Yamazaki, Akiko Yamazaki, Mai Okada, Yoshinori Kuno, Yoshinori Kobayashi, Yosuke Hoshi, Karola Pitsch, Paul Luff, Dirk vom Lehn, and Christian Heath. 2009. Revealing Gauguin: Engaging Visitors in Robot Guide's Explanation of an Art Museum. In *Proceedings of CHI'09*. ACM, New York, 1437–1446.

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