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Elkhuizen, Willemijn; Love, Jeff; Parisi, Stefano; Karana, Elvin

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On the Role of Materials Experience for Novel Interactions with Digital Representations of Historical Pop-up and Movable Books

Willemijn Elkhuizen
w.s.elkhuizen@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Jeff Love
j.s.love@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Stefano Parisi
S.Parisi@tudelft.nl
Delft University of Technology
Delft, The Netherlands

Elvin Karana
e.karana@tudelft.nl
Delft University of Technology
Delft, The Netherlands

ABSTRACT

Direct interaction with cultural heritage (CH) artefacts is frequently unavailable to visitors, offering an opportunity for HCI designers to explore integrating material aspects into digitally-mediated encounters with CH artefacts. We argue that a thorough understanding of the material experiences of CH artefacts can open a novel design space, enabling engaging and meaningful interactions with digital representations. Capitalising on this potential, we present a user study where we systematically explore the material experiences of historic pop-up and movable books. Our analysis identifies five key material qualities to inspire augmentation: fold-ability, slide-ability, tear-ability, age-ability, and print-ability. Highlighting how these material qualities can inspire novel interactions with their digital representations, we present two extended-reality (XR) prototypes of a CH book. With our work, we present HCI designers with a novel approach on designing CH experiences, firmly rooted in materiality, challenging the prevalent paradigms of 'technology-driven' or 'as-realistic-as-possible' sensory experiences often found in CH-HCI.

CCS CONCEPTS

• **Human-centered computing → User studies**; *Mixed / augmented reality*; *Virtual reality*.

KEYWORDS

Materiality, Materials Experience, Cultural Heritage, Books, Mixed Reality, Virtual Reality

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1 INTRODUCTION

Galleries, Libraries, Archives, and Museums (GLAMs) have long been welcoming environments to deploy and test novel Human-Computer Interactions (HCI) (e.g. [35, 81, 129]). In recent decades, this has led to the introduction and evaluation of a wide range of new technologies in these contexts, from Augmented Reality (AR) (e.g. [5, 65], haptic devices (e.g. [35, 81]), Internet-of-Things (IoT) (e.g. [102]) to Artificial Intelligence (AI)-powered (e.g. [44, 77]) interfaces. Besides technology driven innovations, researchers have developed numerous frameworks, tools, and guidelines to support the design of CH experiences for e.g. search and discovery (e.g. [67, 77]) as well as engagement and (informal) learning [40] focused on (subgroups of) GLAMs' diverse audiences such as children and visually impaired ([1, 11, 31, 54]), some with an emphasis on involving them and other stakeholders in co-creation (e.g.[102]).

GLAMs hold vast collections of cultural heritage (CH) artefacts which offer individuals the potential to experience past and present cultures using primary sources. However, due to the objects' delicate and valuable nature, visitors and researchers are often deprived of the opportunity to experience most of the material qualities of these artefacts through touch, sight, and other senses, sensory perceptions which directly influence the meanings, emotions, and actions elicited from people in the interaction with (materials and) artefacts, i.e., *materials experience* [47]. An artefact's materiality can also lead to multiple valid narratives, framed as *relational materiality* [91], which emphasises that experiences are influenced by one's expertise and perspective, including non-authoritative voices. The latter is also of key relevance in recently intensified debates and efforts around inclusivity (e.g. [58]) and decolonisation of heritage collections (e.g. [79, 80]). Furthermore, the rapid (3D) digitisation of CH collections also profoundly affects our experience of them. This "dematerialisation of material culture" [106] also introduces a risk of information loss on artefacts' physical characteristics. In short, the lack of material experience with originals, combined with its rapid dematerialisation, and its potential for plurivocalism, warrants a specific focus on material experiences of CH artefacts, specifically in designing digitally mediated cultural heritage experiences.

Although materiality and materials experience are discussed in various case studies by people working in CH and CH-HCI (e.g. [19, 22, 23, 35]), the process of how material qualities of artefact(s) get selected for augmentation has received relatively little attention. We contend that material experiences of CH artefacts can be better understood, planned for, and subsequently better translated into interactive, digital experiences. This direction opens up a new design space, which offers the potential to design more engaging and meaningful CH experiences built around artefacts' material experiences, rather than being technology-driven, or striving to 'just' be as-realistic-as-possible.

In this paper, we take the materials experience understanding as a foundation to analyse cultural heritage artefacts and to inspire novel digital experiences of them. We propose a methodology to characterise the material experience of CH artefacts and use its outcomes to design novel interactions with CH artefact representations. This methodology builds upon the material driven design method [64] and experiential material characterisation toolkit [16], both developed and validated for the context of novel material development. As demonstration of how the systematic characterisation and design exploration of the material experiences could be manifest, we offer a case study attuned to historical pop-up and movable children's books. Pop-up books are defined as "books, usually for children, in which elements of a picture spring out at the reader when the pages are opened or a tab is pulled" [121], within the (more general) category of movables, defined as "books, usually for children, having mechanisms that move, or are moved by the reader" [121]. In these books, paper – sometimes in combination with other materials – is employed in diverse ways to create a wide range of enriched reading experiences, for instance through dynamic visual effects and elements that can be touched and manipulated. As the originals are generally very fragile, access to them in library special collections is often limited. Moreover, their structural complexity and dynamics make them unsuitable for commonly employed book digitisation approaches, which reduce each page to a static image, and/or machine-actionable text files [50]. These specific (dynamic) characteristics therefore make them intriguing candidates for alternative forms of digital augmentation and an excellent case for exploring materiality of CH. More specifically, pop-up and movable books lend themselves to a study of material experience design due to their 1) extensive and diverse performative potential, 2) visual dynamics (temporal materiality), and 3) their fragile nature (making actual physical interaction difficult). Furthermore, our choice was opportunistically driven, as the national library provided us access to this (historical) special collection.

2 RELATED WORK

2.1 HCI for Cultural Heritage Experiences

Ongoing research in museum studies, museum experience design, and CH-focused HCI tackles topics such as understanding museum visiting styles and visitor motivations [41, 128], which (HCI) designers subsequently adopted in creating and/or evaluating (digitally-mediated) CH experiences (e.g. [90]). Yet, others researched (and involved) audiences and stakeholders in support of designing effective (personalised) CH experiences (e.g.[1, 54, 97]). Continuous technological development, such as in connected micro-electronics (e.g. [88, 102]), head-mounted displays (e.g. [36, 120]), haptic devices (e.g. [35, 129]), and artificial intelligence (e.g. [77]) nowadays provide HCI researchers and designers with an elaborate toolbox to re-enact, enhance, and enrich performances with cultural heritage, through visual, tangible, and/or multi-sensory augmentation. Concurrent with the introduction of (interactive) technology in the GLAM context, numerous guidelines (e.g. [11, 31, 54]), design and evaluation frameworks (e.g. [20, 30]), and toolkits (e.g. [102]) have been proposed with an aim to support the design of engaging and meaningful CH interactions.

The number and diversity of case studies make it challenging to discuss even recent technological interventions for GLAM experiences in detail, but an expansive overview of interactive museum experience design up until the past few years is provided by Hornecker and Ciolfi [57]. They distinguish three interaction paradigms with acknowledged overlap among them: 1) tangible and embodied interaction (TEI), 2) extended reality (XR), and 3) multi-sensory interaction (MSI). The TEI paradigm builds on 'Tangible Bits' [61] along with the notion of 'Embodied Interaction' [37] operationalised in e.g. the Tangible Interaction Framework [56] and associated tools [55], also finding specific application in CH context. More recently, Petrelli et al. [102] have developed and evaluated a tangible interaction authoring toolkit for CH contexts to support co-design across various expertise levels. Within the TEI paradigm Duranti et al. [38] further break down object- and gesture-based interactions by intent into 'smart replicas/originals', 'symbolic objects', 'codified gestures', and 'performing gestures'. Moreover, they suggest two design strategies to either embed or embody intangible values into tangibles [38]. We find that many examples of TEI reside in the symbolic objects/codified gestures category, and these seldom take account of original artefacts' material qualities in their interactions; e.g., using smart replicas to trigger audio (e.g. [34, 88]) and using facial expression or body postures (e.g. [76, 77]). However, there are some noteworthy cases that do draw inspiration from artefacts' material qualities to construct interactions, for instance by creating tangible controls which mimic (part of) the physical layout and/or interaction sequence (e.g. [24, 86]).

XR experiences also vary in the extent to which materiality and materials experience play a role. In most cases the materiality of the CH artefacts remains separate from the interaction, kept at a distance by, for example, the use of a device to direct visual attention (e.g. [29, 65]) or else remanded to features of a visual overlay (e.g. [87, 127]). When experiences move towards the multi-sensory interaction paradigm, interactions are more inspired by the material experience of the artefacts/space (e.g. [120]). Despite various cases studies of multi-sensory VR for CH, Marto et al. [89] conclude the consistency across and documentation of cases is too limited to provide any meaningful overarching design guidelines or other recommendations.

Case studies falling in the multi-sensory interaction paradigm tend to imitate the 'original' multi-sensory experience (e.g. [36]), or use sensory modalities to complement (largely) visual experiences of artworks (e.g. [108, 129]). One notable case in this context is the Multi-Sensory Prayer Nuts experience [19], which takes a comprehensive approach to the materials experience of medieval prayer nuts by addressing multiple aspects of their materials experience, such as their olfactory and tangible qualities, their role in devotional performances, and the intent to elicit a calm and meditative state. Our understanding of how people and computer-driven machines interact in the field of CH – as in many other domains - remains an ongoing process of particular interest to creators of socio-technical systems (e.g. [31, 54, 56, 103]).

2.2 (Temporal) Materiality and Materials Experience in HCI

In the past decades, alongside the ubiquity of (touch)screens representing relatively dematerialised interactions via graphical user interfaces (GUI), HCI researchers have given increasing attention to the material aspects of HCI (e.g. [63, 130, 131], also see recent overview in [93]). Initially, the material focus was on its potential to make computation tangible, for which foundational groundwork was laid in the work of Ishii and Ullmer in 'Tangible Bits' [61], and later extended in 'Radical Atoms' [60], which posits dynamically adaptable 'Computational Composites' [125]. Jung and Stolterman suggested a materials probe toolbox [62] as a means to inspire novel interactions to link digital and the physical worlds. In line with this thinking, many scholars argue in HCI that physical material experiences should support and be considered together with the (digital) interaction experiences and move beyond superficial form-giving metaphors (e.g. [47, 130]). To help operationalise this thinking, Giaccardi and Karana [47] introduced four experiential levels in everyday materials experiences: sensorial (i.e., how materials are sensed), interpretive (i.e., meanings evoked by materials), affective (i.e., emotions elicited by materials), and performative (i.e., actions elicited by materials). Karana et al. developed a method [64] and experiential characterisation toolkit [16] as parts of a systematic approach to study materials experience through a lens of these four experiential levels.

With the advent of shape changing [105], smart (e.g. [3]), augmented (e.g. [82]), ageing (e.g. [107]), and living (e.g. [52]) materials, there is an emerging design space in HCI to study the dynamic and temporal natures of experiences with materials. The notion of temporal materiality has been experimentally explored by Vallgarda et al. [126], who organised temporal material experiences into voyeuristic, vicarious, and visceral experiences. Though these framings and explorations are primarily geared toward novel material development, we argue that the underlying ideas are also applicable to the study and augmentation of temporal materiality and temporal material experiences of cultural heritage artefacts, where we deal with varying timescales that affect our materials experience (e.g. slow processes of ageing and degradation vs fast timescale at 'use' time).

2.3 Materiality in the Cultural Heritage Domain

Materiality is a subject of importance among multiple disciplines related to cultural heritage, including archaeology, art history, sociology, anthropology, and museology. It encompasses research activities such as material provenance investigations (e.g. [85]), material degradation modelling (e.g. [48]), historical reconstruction (e.g. [116]), as well as the study of the meanings of materials [75]. The significance of material experience is particularly prominent within material culture studies, where we find investigations of tactile sensory experiences [49], multi-sensory interpretations [123], and the performative aspects of engaging with cultural artefacts [74, 118], though their findings are not in relation to digital representations or interfaces.

Material experience is also entangled with debates on artworks' 'aura' and 'authenticity' at least since the publication of seminal works by Walter Benjamin [6], where he argues copies lack an aura and that the original's materiality provides a connection to its unique historical and cultural context. Benjamin was speaking of mechanical reproductions (with the advent of analog photography and film), but his discourse on aura remains debated to this day, where it is both extended by proponents and also disputed in relation to the role of digital representations and digital technology in experiencing CH (e.g. [68, 114]). Initiatives like the ReACH declaration advocate for (extensive) digitisation and reproduction of CH, e.g. for documentation and dissemination [26]. They exemplify a model akin to a (digital) emulator for (early) video games and discuss the reproduction of an artwork's original context as well as its importance in conveying multiple meanings and interpretations (cf. Gissen in [26]). Nonetheless, the majority of their examples concern (large) digital image collections rather than more comprehensive representations of individual CH artefacts, which might incorporate more of their material qualities. In line with Gissen, Maurstad [91] argues for embracing the concept of 'relational materiality', where one artefact can have multiple valid interpretations as a consequence of human-material encounters depending on varying (non)-expertise and perspective. We might further add that it compels us to critically evaluate how a designed augmentation may implicitly prioritise one relational materiality over another. This viewpoint is supported by Galani and Kidd [45], who argue against the pervasive use of digital technology solely as a tool for capturing and representing 'literal' forms of materiality. They advocate for a reevaluation of our approaches to designing, valuing, and comprehending material (sensory) encounters more broadly.

2.4 Materiality in Interactive Cultural Heritage Experiences

As part of the material turn in HCI, materiality has (re)gained recognition as a valid and even necessary aspect in developing (digitally-mediated) CH experiences to facilitate understanding of objects, people, and spaces (e.g. [23]). While there are early cases on (multi-sensory) HCI for CH (e.g. [35, 81]), these focus more on usability of novel technologies (i.e. more technology-driven in nature) and less on other design concerns such as the performative aspects of the offered (material) interaction. For example, in evaluating haptic interaction with statues [81], the virtual touching was qualified by participants as 'more interesting' (than no haptic interaction), and 'not realistic'. Many other case studies throughout the years focus - often implicitly – on creating a (as) realistic (as possible) sensorial experience (e.g. [32, 36]). In several recent cases, researchers acknowledge that not all aspects of material experience were (equally) addressed, for instance due to the study's focus (e.g. limited attention to weight, look, and feel of the 3D printed replicas [19]), or to technological constraints (e.g. limited resolution [120]). Yet in nearly all cases, little to no information is provided on how and why certain experiential qualities are selected and implemented.

Even though case studies are sparse in justifying their 'material experience'-related design choices, we do observe that they use CH artefacts' materiality in different ways: 1) there is diversity in the roles played by materiality across case studies. Some cases build on materiality as a source of knowing; the experience revolves around its materiality as a sensory experience (e.g. [19]), or presents (scientific) material knowledge in a human-accessible form (e.g. [124, 127]). Other cases use artefacts' materiality as a grounding for storytelling, where materiality serves as a spatio-temporal anchor to other information or stories (e.g. [29, 66, 88]). We also recognise cases in which materiality serves as a source for artistic reinterpretation. There materiality is sampled, added to, recombined, and/or reified to create novel artistic expressions (e.g. [28, 129]). 2) Experiences address different material life-cycle phases, including foci on materiality in the creation (e.g. [8, 36]), 'use' (e.g. [19]), or care for artefacts (e.g. [127]), which might arguably overlap. 3) There is variety in material performativity, the extent to which an artefact's materiality informs and/or inspires the performance within their digital/hybrid representations (mirrors 'physical engagement spectrum' in [20]), ranging from mimetic (e.g. [19]), to symbolic interactions (e.g. [29]), though we also found cases combining different types of performative interactions (e.g. [120]). 4) Cases differ in material comprehensiveness where materiality might be enhanced, for instance by showing past material states (e.g. [73], or Aztec monoliths in [57]), or through scaling (e.g. enlargements in [115]), feature enhancement (e.g. [21]), the last also recognised by [115] with the application of digital fabrication technology in a CH context. Many other cases seemingly strive to realise an 'as-realistic-as-possible' material representation (e.g. [32, 36, 39]) or rely on a more deliberate sampling of materiality (e.g. [24, 86]). This aspect spans multiple sensory modalities and involves choices not only about visual appearance, but also tactile aspects, weight, sound, or even scent. Finally, cases also differ in their contextual comprehensiveness, where some cases are largely decontextualised (e.g. [59]), others strive to provide extensive, historical contextualisation (e.g. [10, 96, 101]), which Huurdeman [59] also argues is crucial for (material) search and interpretation. Based on the corpus of work reviewed here, we conclude that the emphasis on materiality in interactive CH experiences has consistently been peripheral or unsystematically pursued with a focus limited mainly to material qualities on the sensorial and performative experience level. In our view, there remains more to be gained by studying material experience of CH in a more systematic fashion and employing ways to creatively explore digital (or hybrid) material representations, which also include promoting intuitive *interpretation* and eliciting certain *affective* reactions to materials.

3 A STUDY ON CHARACTERISING THE MATERIAL EXPERIENCES OF POP-UP AND MOVABLE BOOKS

Pop-up books, or the overarching category of movable books [121], have a long tradition. As early as the sixteenth century we begin to see anatomical volumes [17] and astronomical treatises [2] which contain flaps and other movable elements to support communication of complex layered structures and tabulations. The earliest exemplars of children's movable books came about in the eighteenth century with harlequinades [13] and saw renewed periods of innovation and popularity in the 1960/70s [53] up to today (e.g. see Fig. 1). While early versions relied on relatively simple mechanisms such as liftable flaps or rotatable disk elements, contemporary examples can be composites of intricate, connecting, overlaying, and page-extending paper-based mechanisms, which can allow for rich and varied performances with these books (e.g. many featured on [7]). Numerous websites (e.g. [9]) and books (e.g. [18]), and even scientific publications (e.g. [112]) revolve around the craft of paper engineering. References to the materiality of pop-up and movable books can also be found in many other forms of (popular) culture, such as movies (e.g. [69]), tv series (e.g. [72]), (mobile) games (e.g. [113]), theatre [15], and art [43], all of which attest to the versatility of and artistic fondness for papers materiality.

More generally, books – and specifically the codex - have remained a dominant choice to support reading for centuries, which researchers argue follows from their material qualities. In studying medieval manuscripts, Rudy identifies several relevant material qualities of parchment – similar to those of paper – which we might denote as its paint/writability, lightweightness, bind-ability, (modular) reassemble/remix-ability, and age-ability [109–111]. Rudy argues these qualities were exploited to i.a. speed up production, for unification, personalisation, but they can also tell us about readers' physical interactions with them such as kissing and repeat readings. To convey historical books' tangible and haptic performative potential, Green argues for showing 'curational hands as haptic intermediary' in the visual communication on these artefacts (e.g. on social media) [51]. Even today, and contrary to speculative predictions, many readers continue to prefer paper books over digital alternatives, despite the perceived benefits of electronic devices as lighter, more versatile, and having increased functionalities [4]. Spence attributes this to the multiple sensory inputs from acts of reading [117].

Nonetheless, as printed books have proven to (still) be ubiquitous for transferring information, numerous software and hardware tools have been devised to translate the performative material qualities of books to digital representations. Hardware such as tablets and e-readers are portable and allow for actions such as flipping pages, highlighting, annotating, and bookmarking, all interactions rooted in the materiality of (paper) books. Beyond the affordances of digital devices, there have also been explorations into multi-media formats which incorporate forms of written/illustrated heritage, such as interleaving audio, video, and interactive graphic content (e.g. [95, 99, 122]). Other forms of augmented books use paper or books essentially as a token or marker for triggering digital content viewable through a mobile device (e.g. [84, 119, 133]). We might argue that, in these cases, the materiality of the book is only superficially linked to the experience. Other notable cases of book augmentations certainly bring aspects of the material experience, such as an interactive experience featuring a medieval-book [10], linking traditional book making techniques to digital technologies [82], and the creation of novel, hybrid book forms which cleverly interlink their physical and digital elements [104].

To better understand the material experience of pop-up and movable books we conducted a user study consisting of observation and interviews. The study involved recruited participants interacting and reflecting on their interactions with A) ten physical pop-up and movable books, and B) an earlier-developed VR experience (described in [78]) which presented one pop-up, one movable, and two three-dimensional books. VR materials were only presented to participants over 13 years old, as using head mounted displays (HMD) is not recommended under this age by their manufacturers.

Figure 1: Ten pop-up and movable book showing various mechanisms types, which are used as research artefacts (see details in supplementary materials)

In our case study, we focus on the material experience during use time. We exclude experiences associated with practices such as designing/making or conserving such books, although studying these activities would doubtless lead to an even more comprehensive understanding and implementation of their material experiences.

3.1 Research Artefacts

3.1.1 Physical Pop-up and Movable Books. For interaction with physical books, ten pop-up and movable books were used: one hand-made replica of the (19th century) movable book in the VR experience, two books from the 1960s, one from the 1980s, alongside a range of pop-up books currently in print with more or less elaborate pop-up and movable effects (see Fig. 1 and their details in supplementary materials). They were selected to provide a wide range of material qualities (e.g. varying in stiffness, smoothness), and diverse pop-up and movable effects, such as pull tabs, rotational wheels, and 'v-fold', 'boat', 'coil', and 'tube'-style pop-ups (terminology from [18]). Eight of ten books were clearly children's books, while the two others (titled 'Popville' and 'Blue 2') could also be considered targeting a wider age range based on their topic and illustration style.

3.1.2 Virtual Reality Experience. The VR experience centres around four historical books from collections held by the National Library of The Netherlands (KB): a pull-tab-style movable book, a double-page pop-up, an accordion book, and a carousel book (n.b. the latter two are strictly speaking neither pop-up nor movable books, according to [70, 121] but they remain relevant to studying interactions with paper materiality) (see Fig. 2 and details in supplementary materials). To create digital representations, the originals were photographed (used as 3D model textures), and their shape reconstructed through 3D modelling. The experience is set in a virtual library environment, where a central open area is surrounded by bookcases. Initially the four books are presented floating in front of the surrounding bookcases, visible at the four cardinal directions, at a 1:1 scale. Books can be selected by grabbing 'through' them, at which point they disappear then re-appear enlarged, floating or standing, in the central area. Walking in the virtual space can be done by physical movement or using the controller. Users operate interactive elements (such as turning the page or pulling tabs) using the buttons on the handheld controller. A short, textual description of the selected book is also projected above one of the surrounding bookcases. The four books can be interacted with in different ways. The VR experience runs stand-alone on an Oculus Quest HMD, with its default handheld controllers, and was developed in Unity (see also [78]).

3.2 Participants

Participants were recruited among university students and personnel, library personnel, and visitors to a children's book museum. None of them had prior involvement with the research. Informed consent was obtained on the procedure, potential risks, data management, and voluntary participation. All children were accompanied by their guardian throughout the study.

We conducted 34 combined observation and interview sessions. 27 sessions (P1-P27) were conducted with participants over 13 years old, who all took part individually. 15 participants were recruited amongst university students and personnel, and 12 from personnel

Figure 2: Four books featured in the virtual reality experience, in the virtual environment, where (a) is the pull-tab movable book (approx. 8:1 scale), (b) the pop-up book (approx. 8:1 scale), (c) the carousel book (approx. 3:1 scale), and (d) the accordion book (approx. 2:1 scale) (see details in supplementary materials)

at the national library. From these, 21 participants identified as female, six male, and were aged between 23 and 63. In terms of prior experience, the vast majority of participants (24/27) had prior experience with pop-up and movable books. 11 participants stated to have no prior experience with VR, nine had limited experience (i.e. experienced it before), six participants were (more) experienced, and one unknown.

Additionally, seven sessions were conducted with children (P28-P34), accompanied by their guardian. Five sessions were conducted with duos (one child, one adult), and two sessions were conducted with trios (two children, one adult). In all cases, the accompanying guardian partook in interacting with the books. The children that participated were aged between 4 and 10 years old, comprising seven girls and two boys. All nine children were observed interacting with books, but not all interviews were fully completed, due to one participant running off and two participants declining to answer further questions. Nonetheless, all data that was collected was analysed. Eight out of nine children stated to have prior experience with movable books, and three stated to have prior experience with pop-up books.

3.3 Interview questions

The interview questions are based on the material experience framework [64] and inspired by the experiential characterisation of materials toolkit [16], which characterises material experience on four levels: sensorial, interpretive, affective, and performative. Leveraging the flexibility and adaptability of the original toolkit, we used it as inspiration and a starting point for the formulation of a series of open-ended questions on the 1) overall experience, 2) the sensorial, interpretive, affective, and performative material experience of the books, 3) comparison between the physical and virtual books, and 4) demographics and prior experience (see supplementary materials). By deliberately avoiding the limitation imposed by a predetermined set of descriptive terms and scales, we aimed to generate a qualitatively rich characterisation of the lived experience rather than a quantitative assessment. Moreover, through this approach, we have refocused the toolkit to be applied more specifically to cultural heritage artefacts evaluation beyond its current application in evaluating novel and/or underdeveloped material samples. Additionally, for the affective level, we provided participants with an overview of the emotion typology [42] to support them in expressing emotional nuances, rather than a (more) limited set of opposing descriptive terms.

3.4 Procedure

Physical books were presented on a table to be handled in a seated position. For the VR experience, a physical space of roughly 3x3m was cleared and a virtual boundary was set to minimise collision risk. In both activities, participants were observed by two observers and their interactions video recorded by two cameras. For the VR experience, the participant's first-person view was also streamed for the observers to see and recorded. Observers provided instructions and support on mounting the HMD and using the controllers. When needed, additional verbal support was given by the observers during the experience.

The user study for participants over 13 years old progressed in this sequence: participants were invited to interact with one of the two research materials (either physical books or VR experience, randomly assigned) and asked to speak aloud during their interactions. The researchers emphasised to participants that they were free to select and interact with the research materials as they liked. This was followed by questions pertaining the prior experience. Then participants interacted with the other set of research materials (either physical books or VR experience), which was followed by questions pertaining to that experience and questions comparing the two experiences. All interviews concluded with questions on demographics and relevant prior experience. The interviews were audio recorded. The procedure with children had a similar setup, but consisted only of interacting with the physical books, followed by the interview questions. For the sessions with adults, pre-scheduled timeslots of 45 minutes were available per participant, to engage with both the physical books and VR, and subsequent interviews. For the sessions with children, participants were recruited ad hoc, as the previous session was wrapped up. These sessions lasted between 15 and 29 minutes.

3.5 Data transcription, coding, and analysis

Initial transcripts of the observations and interviews were generated using the Microsoft Sharepoint embedded transcription tool and subsequently reviewed and corrected. Transcripts, as well as the video footage were analysed and coded using ATLAS.ti software, following a theoretical thematic analysis approach [12]. Thematic codes are structured under the four levels of the material experience framework [47], also referencing pertaining either the physical or virtual book(s). A first round of coding was conducted on the data of participants 1 to 3 by the first author, which was subsequently reviewed and revised by all authors. This then formed the basis for coding the remainder of the interview data, but leaving room to add new codes as they emerged. The final set of codes was reviewed and revised (incl. regrouping, rephrasing) by the first author following the material experience framework. Codes were then clustered into material quality categories by the first and last author. This clustering into material qualities built on the material qualities recognised by Rudy [109–111], with respect to material qualities in manuscripts/books in general, while others emerged from the coded data, as they pertain the specificities of pop-up and movable books. Subsequently, a summary was created for every material quality, consisting of a diagram (from [16]) and short textual descriptions incorporating participant quotes. In the diagram, experiential characteristics are the sorted along the four experience levels, and they are interlinked based on mentioned or observed connectedness as interpreted by the researchers in the data analysis phase.

3.6 Results

3.6.1 Performativity of Pop-up and Movable Books. In the observation study, a rich variation of performative actions were observed when interacting with the physical books. These performative actions are summarised in Fig. 3, organised by interactive element, e.g., pull tabs and rotation wheels. We also observed varying temporal patterns associated with different interactions, such as multiple fast repetitions, versus slow or partial actions. A characterisation of these temporal patterns is also added per interaction element in Fig. 3. We observed a more limited set of performative actions, with the pop-up and movable books in the VR experience. These are visualised in Fig. 4, also organised by interactive element, including their temporal characterisations.

3.6.2 Material Qualities of Pop-up and Movable Books. The material experience characterisations were clustered into five distinct material qualities that are exploited by pop-up and movable books: fold-ability, slide-ability, tear-ability, age-ability, and print-ability qualities; the last two (indirectly) derived from Rudy [109–111]. The material experience we have associated with the fold-ability and slide-ability qualities rely on a paper's cut-ability and (sometimes) glue-ability, to allow shaping into endless imaginable configurations (at 'design' time). However, we deemed these qualities subordinate to the fold- and slide-ability. The characterisations on the four material experience levels, are summarised per quality in a diagram, such as Fig. 5 illustrates for fold-ability (see others in supplementary materials). The diagram distinguishes characterisations which were mentioned in relation to the physical book (coded in blue and with circles), virtual books (coded in red and with stars), or both (coded in green and with squares).

Fold-ability. This relates to the ability of pop-up and movable books to unfold from a flat stack to a three-dimensional scene triggered by a page turning motion, which participant 3 (P3) described as the book becoming a "3D World that moves when you like slightly open and close the pages". Fold-ability is associated with emotions such as positive surprise, anticipation (for the next page), joy, and amusement. Moving the pop-ups creates dynamic visual effects and evokes associations of nostalgia, explosions, and "unwrap[ping] the presents" (P10). It triggered performative actions such as repetitive opening and closing, and moving the book and body around in order to further visually explore the book, e.g., by "rotating the book around or rotating myself around to see all the corners" (P3). However, repetitive mechanisms also led to boredom, which in turn led to fast turning or skipping of pages, as illustrated by P21 saying "it's nice to see how it's built up, but after three pages, it doesn't surprise you anymore".

Slide-ability. This relates to the ability of paper parts to slide in front and behind one another by activating movable mechanisms. This quality is associated with performative actions such as pinching and subsequently pulling, rotating, or 'wiggling'. Participants experienced it as playful and nostalgic – even recalling specific books from their childhood – and interpreted the effects as inviting, mysterious, and attractive, such as P13 wondering "how far it will spin out" and enticing them to "keep going until it meets the end". It leads to emotions such as positive surprise, sensory pleasure, amusement, but also fear (of overlooking something), and confusion (what to interact with). While their actions create dynamic visual effects, VR participants emphasise the lack of sound and force feedback. Simplicity and repetitiveness of books also evokes emotions of boredom, as P2 points out that pulling the "string of paper was super underwhelming" stating they didn't feel they need VR to "just pull a piece of paper."

Tear-ability. This relates to the quality or rather risk of paper to tear, and thereby be damaged, which was mentioned by many adults in relation to interacting with the physical books. For multiple participants this led to careful performative actions such as partially or slowly turning a page, not applying force, and at times refraining from touching parts of a book. Participants were guided by sensory cues such as feeling friction, hearing scratching paper or by their perception of damage risk, such as P27 posing the question "can I now push through this, or am I breaking it?". It reinforces their supposition that paper is fragile and that pop-up books are expensive and delicate. This led four participants (with experience in public libraries or their own children) to conclude these books are not (very) suitable for children due to concerns about breakage, as P3 states: "I wouldn't enjoy it as much [with a little child] because then I would just be terrified like: 'Don't break this' ". In contrast, others displayed less apprehension (adults and many of the children), engaging in more careless interactions such as flexing the page, pulling the pop-ups apart and other fast and rougher actions, though seemingly not with the intention to break them. Notably, this material quality was absent in the VR experience. P3 explains that: "[the book] in VR cannot really break, and if it breaks it, doesn't have any [. . .] actual repercussions. You can just reset it", which stands in contrast to handling the physical books.

Age-ability. This relates to the quality of paper to age. Readers mentioned signs of ageing such as folded edges, faded colours, smell

Figure 3: Overview of 33 distinct performative actions with physical pop-up and movable books observed during the user study. Actions are clustered by interactive element type with a description of observed temporal patterns

Figure 4: Overview of fourteen distinct performative actions with pop-up and movable books in VR observed during the user study. Actions are clustered by interactive element type with a description of observed temporal patterns (if any)

(of old books), changes in sound (crispness), and reduced stiffness, thereby (indirectly) referring to (past) performative actions such as page turning, pinching, and other inherent ageing processes. P16 refers to the aged appearance of the books in VR as "so you see [...] the imperfections here", leading them to conclude originals were scanned rather than it being computer designed. The ageing quality leads to interpretations of items being either old or new, authentic, broken, faded, and fragile. Perceived age also enhances the appeal of interaction, as P6 voices: "It's always a privilege to be able to touch materials because you're not always allowed to [...]. These [...] are quite recent, but if you have [...] antiquities [...] then you're not allowed, and that would make it more fun to be able to touch a pop-up book". The dichotomy between the apparent age of the depictions and the perceived ageing of the material is noted in the virtual books, as "you don't really get the same kind of the smell of an old book or [...] pages being kind of ripped at the edges [...] but you still see it in [...] the content of the book, that it's historical." (P3).

Print-ability. This relates to the ability of paper to be printed, with text, colours, images, and even special effects (e.g. use of metallic and iridescent foils). Performative actions such as turning pages, moving the book around, zooming in, reading, showing and explaining to others, all (indirectly) relate to the print-ability of the paper. Participants frequently commented on the colourfulness of books, as well as on dull or "wrong"(P5 and P12) colours in the VR experience . Print-ability resulted in diverse interpretations, including perceptions of imagery as old-fashioned, beautiful, attention-grabbing, and immersive. P11 highlighted that enlargement in the VR allowed them to "explore and see everything and all the small details because it's up close, and you can get a lot closer to it than for example [a] real book". Print-ability triggered sensory pleasure, calmness, and amusement. The use of shiny, metallic, or otherwise textured effects in physical books also elicited positive emotional responses, such as happiness. However, it could also lead to confusion due to the experience being overwhelming, occasionally inhibiting slide-ability and associated performativity: "Sometimes I'm not entirely sure [...] which thing to pull because some of them have multiple things you can go on. [...] I pulled the hat. But, [...] I may have not caught on to that if I [had not] looked closely enough." (P13).

3.6.3 Other Observations on the Experience and Usability of VR and Physical Books. Other salient observations from the user study relate to differences in interaction between the physical and virtual books (e.g. their intuitiveness), and differences between users. For physical books, no explanation was needed on the overall working of the books or their mechanisms, even for the youngest participants. In contrast, the VR experience required instructions, as well as extensive and frequent support, to guide nearly all participants through the experience. We also found that in almost all the cases the VR was experienced, participants immediately drew comparisons between the material qualities of the virtual books and physical books (or paper in general), regardless whether they had experienced the physical books before or after the virtual ones (meaning also no order effect was observed in our user study). This might be explained by the fact that nearly all participants had prior experience with pop-up and movable books, which then seems to serve as an implicit reference for the VR experience. A clearly observable distinction between adults and children alongside adults

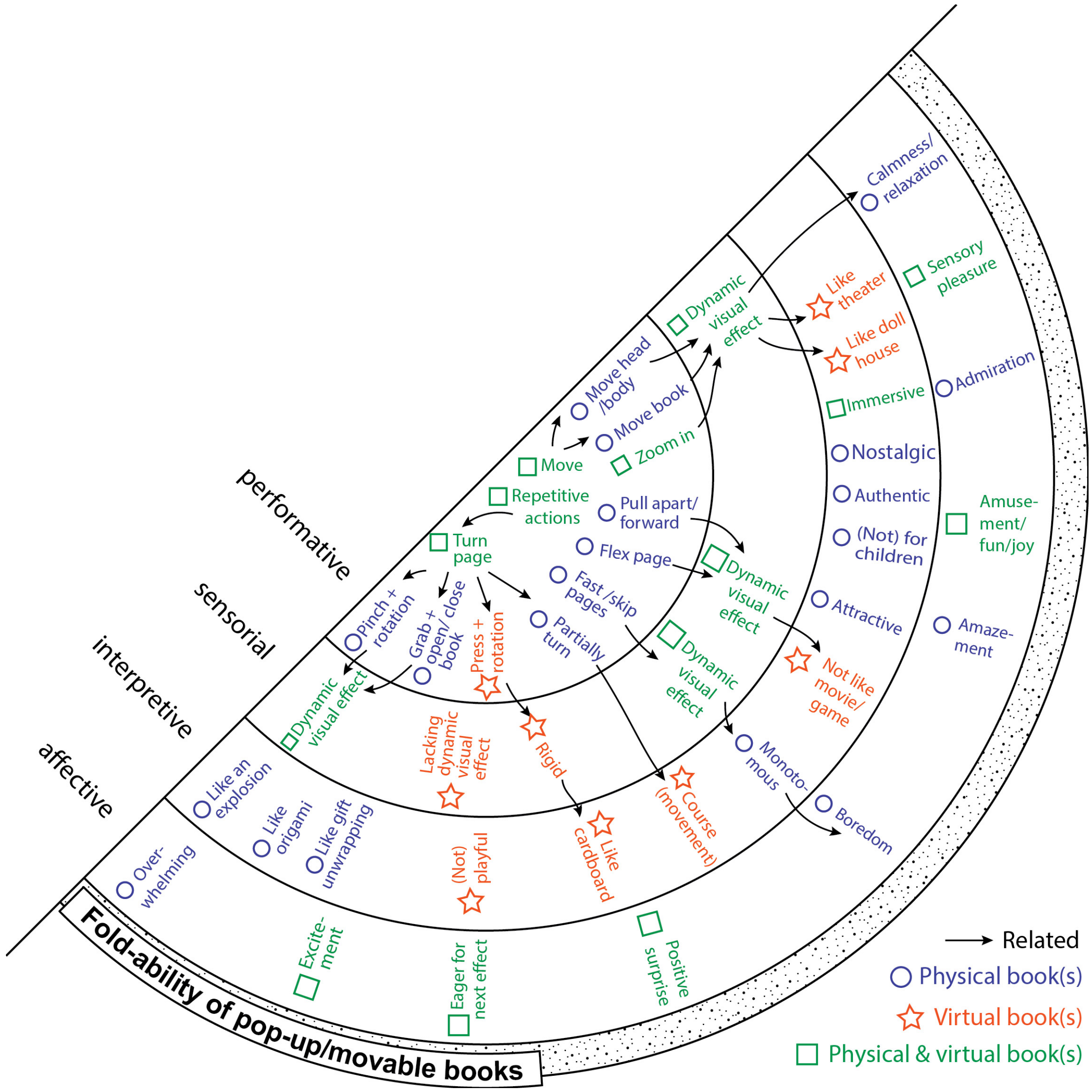

Figure 5: Material experiences characterisation, related to the fold-ability of pop-up and movable books, structured and linked across the four levels of material experience (diagram adopted from [16]). The characterisations are coded in relation to the physical books (coded in blue and with circles), virtual books (coded in red and with stars), or both (coded in green and with squares). Characterisations which could be interlinked from the interviews and observations (based on close or co-occurrence) are connected through arrows.

was that the latter led to many more social interactions. With children, the books triggered accompanying adults to read books aloud and pose elaborate, back-and-forth question and answer sessions. Their interactions also focused much more on the content of the books than did solo adults. Several participants commented that they believed the content was targeted toward children. We infer that they largely ignored the content because of this and instead focused more on the form, structure, and dynamics of the books and rarely engage in reading. Adults may also be more conscious of the experimental setting (i.e. the reading aligned with commonly occurring child-adult interactions). Besides the material experience (discussed above), comments about the experience related to: the story in the books, the synergy between story and the interaction mechanisms, the suitability and judgement of the physical and virtual environments (e.g. either liking or disliking the virtual library environment), affordances of VR technology (e.g. allowing you to do less or more than in reality), and usability aspects of the VR experience (e.g. confusion/doubt/frustration with controllers and use cues).

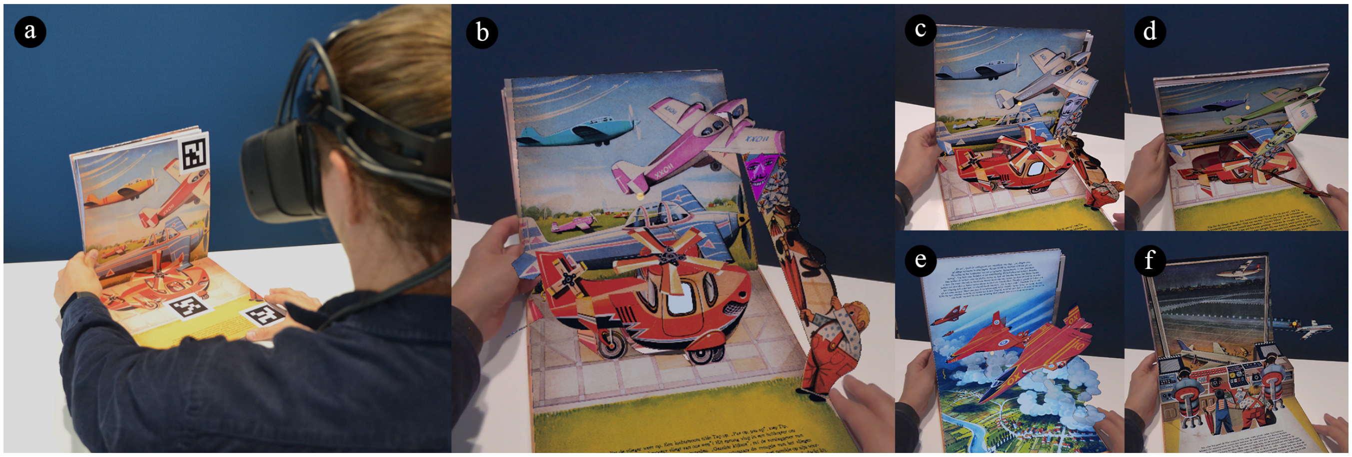

Figure 6: XRLibris - an extended reality prototype with interactions and effects inspired by the material qualities of pop-up and movable books. (a) Shows the 'dummy' book with printed QR codes (and decorative illustrations) as it is visible to onlookers, and (b-f) the first-person view as seen via the HMD showing the overlaid and synchronised pop-up and movable effects. (b-d) Show a fold-ability enhancement by the (randomised) colour-changing effects linked to the opening angle of the book. (e) Shows an age-ability enhancement through the simulation of the original appearance of a page, which ages with prolonged interaction. And (f) shows a tear-ability enhancement as the aeroplane tears loose from the page and flies away. ©1964 Vojtěch Kubašta (original book) [71], adapted with permission.

4 HCI APPLICATIONS

To exemplify the application of material qualities obtained from our study in the design of novel interactions, we present two extended reality (XR) prototypes — one mixed reality (MR) prototype developed by the first author, and the other a VR experience delivered as the final outcome of a six-month master graduation project [46]. The MR prototype uses the Varjo XR-3 HMD, and the VR prototype the HTC Vive Pro™ HMD, both combined with external position trackers (SteamVR™ 2.0) for (more) stable position tracking. Both prototypes are based on the book 'Tip+Top Go Flying' by Vojtěch Kubašta (1964) [71], which was initially digitised via photography (library collection copy), but ultimately through flat-bed scanning (non-collection item). The latter served as the texture, but also as traceable template for the 3D model, which was created in 3D modelling software Blender. In both cases, animations and interactions were created in Unreal Engine (version 5.2). In both cases the goal was to produce an XR prototype with embedded material experiences.

4.1 XRLibris - a Mixed Reality Prototype

Two insights from the user study inspired the overall concept of the MR prototype: the observed difference between the physical and virtual pop-up books in interaction diversity and temporal characteristics, as well as the difference in tactility, directness, and intuitiveness of interaction. The prototype consists of a 1:1 scale physical 'dummy' book with flat pages, QR codes and (decorative) illustrations printed on every page (see Fig. 6a). As the user rotates the book and turns the pages, the virtual content (pop-ups) is projected onto the pages, following the physical pages' relative position, mirroring the *dynamic visual effects* of the original book, and enabling all ***fold-ability*** associated performative actions (see Fig. 6b). To activate the movable parts of the book (pull tabs) we relied on the built-in eye-tracking functionality of the HMD. Vision-based hand tracking was initially envisioned – being more in line with the original interaction – but turned out to be less reliable in its tracking (thereby unfortunately not enabling *pinch + pull*, *rotate (wheel)* and *wiggle* interactions, clustered under ***slide-ability***).

Moreover, we explored enhancing several material qualities with complementary visual and auditory effects. Each of these is featured on one two-page spread. These enhancements are intended to trigger (increased) performativity, such as *repeated open-and-closing of the pages* (***fold-ability***). On page four, several parts of the depiction change colour (randomly), synchronised with the page opening angle (see Fig. 6b-d). With this, we aimed to enhance users' *positive surprise*, *amusement*, and *eager(ness) for next effect* (***fold-ability***). Although these experiences were associated with the fold-ability quality the enhancement also (potentially) affects the experience of the ***print-ability*** quality, as we now amplified its dynamic, colourful appearance beyond the original's printable capabilities (interpretations such as it having *dull/wrong colours* or being *old*). To enhance ***age-ability***, one page was made to look new (see Fig. 6e), and with prolonged interaction the page slowly yellows and starts showing signs of use in the form of fingerprint marks and staining (performative actions such as *(no) grabbing the edge*, leading to *(no) wrinkles*, *(no) wear signs*, *(no) use signs*, and (the absence of) *visual imperfections* and *faded* colours). On the final page, we highlighted the ***tear-ability*** quality of paper, where triggering the pull tab (via eye-tracking) results in a *ripping sound* and visible *tearing* as a part (an aeroplane) comes loose from the page and flies off (see Fig. 6f).

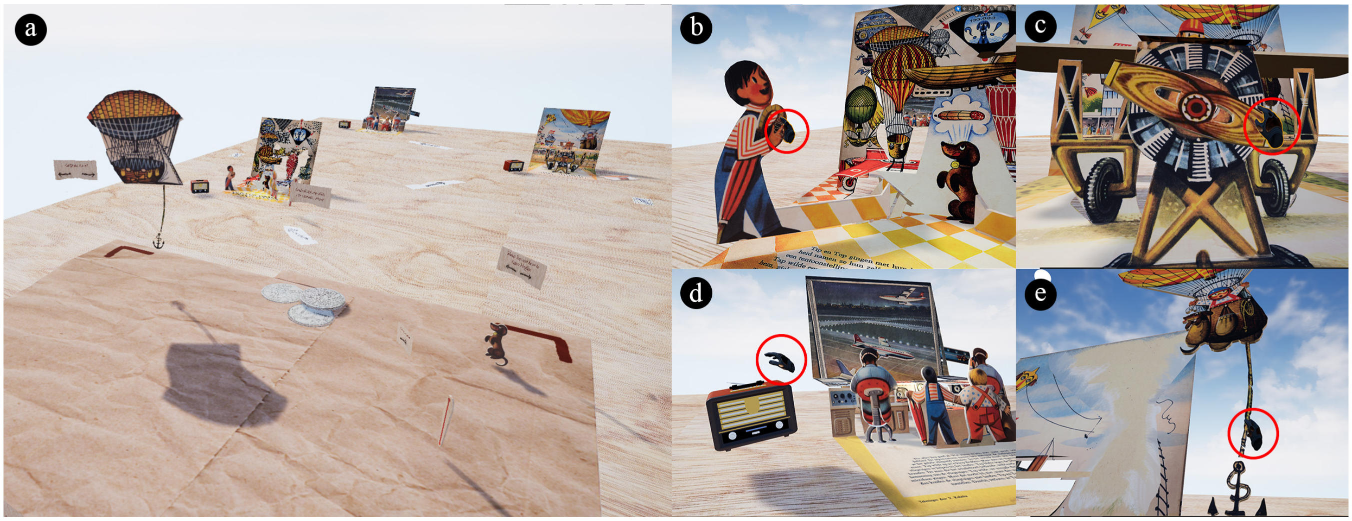

Figure 7: Pop 'N Read - a virtual reality prototype with interactions and effects in part inspired by the material qualities of pop-up and movable books. (a) Gives an overview of the complete virtual space; the foreground shows a practice area where users interact with various elements (demarcated by brown paper), and the background shows three prototyped pages as separate scenes (n.b. experience is not seen from this perspective by the user). (b) Shows the user grabbing and sliding one of the figurines. (c) Shows the user rotating the aeroplane rotor. (d) Shows the user dropping a radio. And (e) shows the user grabbing (and pulling) the rope of the hot-air balloon. In (b-e) the hand, signifying the location of the user's controller, is highlighted with a red circle. Note that the images were captured via Unreal Engine desktop interface (not via the VR headset), incl. staging the virtual hand positions, for clarity reasons (i.e. it allows capturing other/wider fields-of-view) ©1964 Vojtěch Kubašta (original book) [71], adapted with permission.

4.2 Pop 'N Read - a Virtual Reality Prototype

The two main departure points for this prototype were: 1) that many participants mentioned the scaled-up VR pop-up books to be very fascinating and enjoyable (we infer these experiences relate to the ***fold-ability*** and ***print-ability*** material qualities of the books), and 2) the observation that many people did not engage with reading the books (*(not) reading* as a performative action relates to the ***print-ability*** of books). Therefore, the VR prototype explored translating their material experience to a larger-than-life scale, and linking material experiences to narrative engagement, additionally drawing from narrative engagement frameworks by [14, 20]).

The VR experience is staged on a large wooden table surrounded by blue sky (Fig. 7a), where three pages of the book are presented side-by-side at a larger-than-life scale (figurines are life-size). A 1960's radio play adaptation of the book is used to support the reading experience in the form of audio narration (*read out loud* from ***print-ability***). Selections of the story narrative connected to the scene can be triggered by interacting with various elements (*press + pull* and *rotate (wheel)* from ***slide-ability***). Part of the interactions are mimetic to pop-up book interactions such as moving the figurines (Fig. 7b), rotating an aeroplane rotor (Fig. 7c), and pulling a tab. These speak to the ***slide-ability*** qualities of paper, while other interactions within VR were more symbolic to pop-up book interactions, such as dropping a radio to start narration (Fig. 7d), or grabbing a rope (Fig. 7e). The *ripping sound* of paper and visible *tearing* and associated *fear of damaging* were used and linked to heightened narrative fear (of flying off and dying) (Fig. 7e). Other visual and auditory elements of the experience also matched the material qualities of the pop-up book/paper such asadding *wrinkles* and *visual imperfections* to text signs and speech balloons (not visible in Fig. 7) (***age-ability***), and an overall visual and auditory aesthetic to match the *old* and *nostalgic* associations related to ***print-ability***).

Other elements draw from the materiality of the book's content or historical context (e.g. sounds of an aeroplane engine, background music).

5 DISCUSSION

5.1 Opportunities and Implications of Expanding Materials Experience in HCI

5.1.1 Broadening the Application of the Materials Experience Framework. The prototype XR experiences of a pop-up and moveable book presented here serve as proofs-of-concept combining and adapting the Materials Experience Framework [47] with associated tools (e.g. [16]) to the Cultural Heritage Human-Computer Interaction (CH-HCI) context. The approach extends the framework's conventional application area of emerging and/or underdeveloped material development to encompass materials experience characterisation of current and historical materials. This both broadens the framework's scope and underscores its versatility. We contend its application in CH contexts could be further extended to the characterisation and augmentation of numerous artefact collections and potentially even CH sites (e.g. [96]). As materials experience is also relevant in many other augmented experiences, the relevance of this approach might also extend beyond Cultural Heritage applications and potentially find resonance in diverse domains, such as medical and industrial training applications. Further case studies could also serve to improve and otherwise validate the merits of adapting the material experience framework for CH artefacts and beyond.

5.1.2 Towards a Material Experience Driven Design Methodology for the Cultural Heritage Context. This paper outlines one possible methodology supporting the design of engaging and meaningful CH experiences: taking the experiential material characterisation of cultural heritage artefacts (in this case pop-up and movable books as a starting point), and using this to inspire novel, digitally-mediated interactions. In our case study, we used observation and interview methods as a means to elicit materials experiences from users (specifically through the use of contemporary surrogates). Following this, we clustered materials experience insights around five key material qualities (following [16]). These were then used in a creative design phase to prototype two XR experiences. Reflecting on our proposed methodology, we acknowledge that there might be other suitable methods for experiential material characterisation (e.g. relying on historical sources, or involving other stakeholders). Furthermore, we envision drawing more parallels to the material driven design (MDD) method [64], such as formulating a (material) vision, and distilling a couple of contrasting or complementary meanings (e.g., 'modest' and 'provocative', 'active' and 'playful'), to guide further concept development. In the CH context, however, this step might be a two-way negotiation, where the narrative(s) might either emerge from the experiential characterisation and/or be predefined (i.e. you want to use an artefact to tell a specific narrative). Further parallels might be drawn to the MDD method, where tinkering with interactions allow designers to sculpt an envisioned materials experience. Finally, a complete methodology would also require a more extensive, iterative approach to prototyping and testing interactions to verify the resulting materials experience.

5.1.3 Expanding Material Experiences Understanding through Digital Technology. Various materials experiences insights on our user study stem from participants interacting with the earlier-developed VR experience. Observations here proved more telling than viewing participants' interactions with the physical books alone. We believe this is likely due to the VR experience putting (more) emphasis on certain material aspects otherwise taken for granted or not consciously registered by the participants or designer(s) (e.g. the flexibility of the paper or pages lacking signs of wear). As these provided numerous additional insights usable in the design phase, we contend it would be worthwhile to incorporate such explorations (e.g. in the form of evaluating an early prototype) to surface and characterise unforeseen aspects throughout the design process. Thereby, we advocate utilising (early) prototypes for the experiential characterisation of artefacts and their materials, across all levels, but caution for a too narrow focus, of 'merely' evaluating the experience's (sensorial) realism.

Furthermore, extended reality enables us to capitalise on insights which emerged from the experiential characterisation studies and subsequently creatively manipulate the experiential material qualities. This is a demonstration of direct transferal and augmentation of insights relating to material qualities into novel interaction scenarios. The observations and prototypes above further indicate a broader scope for the MDD method, from using digital augmentations to communicate material qualities in a *design process* (as defined by e.g. [3]), to the augmentation of material qualities in *use time*. On top of this, XR technologies present opportunities to modulate spatial and temporal scales, culminating in richer, engaging experiences for users (cf. scaling-up VR pop-up books, and accelerating ageing above). Through XR prototypes we have the ability to fine-tune qualities which intentionally enhance some desirable emotions and associations and, when desired, avoid evoking potential negative associations. One example is the decision to enhance fold-ability by adding dynamic visual effects for the purpose of mitigating boredom evoked by monotonous page turning.

While our interventions have focused on using XR technologies, we believe the materials experience framework leaves open the possibility to design materiality-rooted CH experiences relying on other interaction paradigms. We also acknowledge that there remain fruitful possibilities to craft physical or hybrid interactions with heritage artefacts through other (digital) reproduction methods (e.g. digital fabrication [39, 115]), as well as with the original artefacts themselves through future, non-destructive approaches. Specifically for the case of pop-up and movable, we acknowledge that making physical, paper replicas could be a perfectly suitable solution to experience these artefacts (as-is), and have readers 'consume' copies through use. Yet, we believe that the use of digital technology can also offer new opportunities, that would not be attainable with the original or physical replicas, such as dynamically showing process of degradation, or offering spatio-temporally linked contextualisation. Moreover, we believe that using material qualities as inspiration for novel interactions can offer new pathways to intuitively linking the physical and the digital domain (as also discussed in [103]).

5.2 Challenges of Including Diverse Material Qualities and Their Interrelationships in (CH-)HCI Design

5.2.1 Novel Interactions Inspired by (Interrelated) Material Qualities. Reflection upon the experiential characterisation of pop-up and movable books reveals that material qualities do not function in isolation. Paper's print-ability is fundamental to the dynamic visual effects, which are in turn essential to the materials experience of the fold-ability and slide-ability qualities (one might imagine all the pop-up and sliding elements were just plain white paper). Likewise, the tear-ability and age-ability of paper are closely connected (e.g. torn books might also be interpreted as being more aged). Understanding, articulating, and orchestrating these interrelations become critical for a designer and serve as a compass guiding the creation of engaging and profoundly meaningful interactions for a specific object or constellation of items. Central to this approach is the acknowledgement of material qualities as a pivotal factor within the design equation. Instead of relying solely on intuitive choices, this approach emphasizes that material qualities can exert a direct influence on decision-making processes in the design process.

5.2.2 Material Performativity and (Additional) Pictorial/Textual Opportunities for Inspiring Augmentations. This study centred primarily on the material qualities of paper pop-up and movable books, by inviting readers to handle and experiment with them. Such interaction is not common to all historical items; artefacts such as paintings or sculptures are not intended to be handled. While we expect that people's interactions with heritage artefacts consistently involve all four material experience levels, artefacts crafted from different materials or having different use characteristics demand individual considerations. Additionally, artefacts featuring writing or figurative depictions - such as the books in our case study - may be more conducive to digital augmentation, as they allow leveraging qualities from both their content (i.e. artefacts depicted or described) in addition to the artefact itself. Conversely, objects lacking narrative or figurative components – i.e. the majority of artefacts in (museum) heritage collections – may require additional cues or further considerations for making their materiality intelligible and memorable.

5.2.3 Better Understanding Materials Experience's Role in Engagement and Learning. Significant technical and scientific limitations persist in mimicking human touch and other sensory perceptions in digital spaces. Comprehending, quantifying, and augmenting particularly the sense of touch, smell, and taste, are ongoing fields of research (e.g. [89, 98, 129]), and still relatively poorly understood compared to the senses of vision and hearing, as well as other sensory phenomena such as sensory integration (e.g. [27]) and synaesthesia (e.g. [94]). Moreover, a firmer grasp of which elements contribute to people's understanding and experience of physical object materials would better facilitate digital translations, adaptations, and augmentations.

5.2.4 Ethical Considerations in Designing (Digitally-Mediated) CH Experiences. The case of augmented materiality provides an example of response to a need to compromise or innovate amid primary concerns of CH institutions. Foremost among these is a tension between the necessity to preserve artefacts and the need for visitors to have engaging and embodied experiences with them. Augmentation necessitates making choices in the design process and represents a certain level of editorial or creative control. Decisions on what to augment and how entail a set of choices for adapting them to a new medium. These choices bring with them further questions about authenticity and faithfulness [26, 68] to original objects on top of authorial/creator intentions, if they are known. Moreover, (re)presentation in any form follows from curational choices, and thereby will always effects our perceptual, interpretive, affective, and performative responses. Whether a representation is therefore 'as-realistic-as-possible' or authentic in a perceptual or performative sense might be too limiting, or even futile to strive for. Rather, we propose (in line with Penrose [100]) to aim for 'experiential authenticity', and propose that through our methodology - starting from materials experience characterisation and experiential prototyping of novel interactions - designers can explore alternative pathways to creating experiential authenticity. Along this line, the conclusion whether an experience represents the original artefact, or is a completely new artistic expression, only inspired by a historical artefact, is in part a design choice but also a matter of interpretation, which can differ per stakeholder. Nonetheless, it is important to consider the effect of a digitally-mediated experience on our understanding of the artefact itself, i.e. how the experience might alter our understanding, appreciation, or even care for the original (e.g. as discussed by [25]).

Augmentations rooted in materials experience also introduce more interpretive ambiguity, as opposed to more descriptive and/or factual augmentations. Such ambiguities hold the potential to (co-)design thought-provoking experiences which diverge from the authoritative institutional voice (e.g. [132]) central to debates on inclusivity (e.g. [58]) and decolonisation of CH (e.g. [79, 80]). While opening up the possibility of multiple narratives on artefacts [22], interpretive augmentations confront institutions with challenges on dealing with foregrouding (potentially) controversial CH, which include the potential for – in somebody's view – misinterpretations, or even abuse of CH.

5.2.5 Practical Considerations in Designing (Digitally-Mediated) CH Experiences. Digitisation and development of CH experiences remains an expensive and selective process requiring numerous practical considerations related to e.g. the use context and operations (summarised in framework by [30]), many of which not addressed in this study. For our prototypes we decided to use XR technology for its abilities to enable diverse forms of performative interaction, and manipulation of perceptual aspects of the digital representations, which - in the case of mixed reality - could be also overlaid onto its physical counterparts, and controlled through direct, physical manipulation. Yet, designing XR experiences still has many challenges and limitations. For instance, current options for linking physical and virtual is still relatively limited, mostly relying on (unsightly) 2D markers, or bulky trackers. Other forms of computer vision-based detection and tracking are largely restricted/disabled by manufacturers. This, thereby, also (currently) limits options to dynamically synchronise virtual content onto originals or (3D printed) replicas. The complexity of XR development tools (such as Unreal Engine) also poses challenges on conducting fast prototyping cycles, putting practical limits on the amount of design variations that can be explored, which would otherwise enable to better understand how (small) design choices effect the resulting (digitally-mediated) material experience. Moreover, our study and prototyping activities do not address limitations XR technology imposes on social interactions, which are an essential part of a CH experience (pg. 8-10 in [57]). Enabling social interactions, as for instance observed on between the children and their guardians in our study, would require other or additional technological implementations. This lack of shared, immersed perspective was also observed in (preliminary) demonstrations of our mixed-reality prototypes, as for instance the 'magic' of the virtual overlays and (the effects of) direct manipulation were not well conveyed to onlookers through a connected screen. Nevertheless, we envision that (social) mixed reality presents fresh opportunities for integration in exhibition settings. It has the potential to address existing limitations in VR by enabling intuitive tangible interaction, real-world presence, and having the potential for both physical and emotional social interaction.

We also acknowledge that our prototypes are not fully-fledged CH experiences, mature for implementation in an exhibition context. The prototypes present an exploration into material experience inspiring digitally-mediated experiences, but meanwhile do not address numerous issues relevant to creating a feasible, viable, and desirable CH experience. The prototypes, for instance, were not designed with a specific audience or exhibition context in mind, nor adhere to all guidelines suggested for (interactive) experiences (e.g. offer different levels of engagement [54], or allow to preview from a distance how it works [31]). Also, we might consider that a (conventional) library offers a different context than a museum, catering to other audiences (e.g. (amateur) researchers, or people seeking a quiet study place) with likely other interests and visiting motivations [41].

We therefore conclude that much more work in this area remains to be done, in designing but also critically evaluating [33, 89] the effectiveness and feasibility of new CH experiences.

5.3 Limitations and Future Work

5.3.1 Using Contemporary Artefacts as a Proxy for Material Experiences with Historical Artefacts. Our study utilised contemporary physical (and digital) pop-up books as surrogates due to unavailability of original historical artefacts. This necessitates some caution in interpreting observed materials experiences, in particular regarding surrogates which were in part more contemporary and technologically advanced than the original artefacts. This has the potential to invite critique of the artefacts based on modern norms rather than those of their times. On the other hand surrogates, where available, are inexpensive to work with and for the most part convey the materials experience of the originals. CH artefacts lacking accessible surrogates for reasons such as lack of funds, lack of priority, or copyright may demand alternative approaches to characterising their material experiences.

5.3.2 Familiarity with Artefact Category. Participants in our study had prior experience and familiarity with pop-up and movable books, which informed their actions, associations and emotional responses. Users' frames of reference and background knowledge will certainly vary and will likely be more limited for large proportions of heritage collections, potentially leading to more diverse and unguided interpretations. This potentially offered us a clearer and more consistent experiential material characterisation than would be the case for more unfamiliar artefact types.

5.3.3 Incorporating other Stakeholder Perspectives throughout the Design Process. The scope of our study was solely on 'use' time interactions with pop-up and movable books, to the neglect of other possible sources for interpretations on their materials experience. Future studies could do well to broaden the focus to include interpretations of materials experience between different stakeholders, in particular curators and conservation specialists but also authors of paper-engineered books, to elaborate further on the role of materiality in e.g. the design of and care for such artefacts. Concurrently, the CH experiences would benefit from further stakeholder involvement throughout the design process, as advocated in co-design and participatory design approaches for the CH context by others (e.g.[22, 83, 92]).

Finally, the approach taken in this study is more open-ended than definitive. The evaluations of the prototypes on their material experience, by users but also other stakeholders such as curators, are planned as future work by the authors. Increased stakeholder involvement and the development of suitable approaches for (iterative) evaluations are an essential next step in the development of a materials experience rooted design for the CH context. Such evaluations could then potentially also shed light on the role of materials experience in learning and engaging (with CH artefacts) and how best to facilitate this in GLAMs and related settings. Future work focusing on material experiences and creative digital translations of them will continue to support designers in the considerations of augmenting CH artefacts' material experiences.

6 CONCLUSIONS

The studies discussed above provide insights into the material experiences of adults and children interacting with CH artefacts, particularly pop-up and movable books. By proposing an application of the Materials Experience Framework [47] for CH artefacts, we were able to capture rich descriptions of their material experiences, and we have characterised these experiences across sensory, interpretive, affective, and performative levels, allowing us to draw inspiration for designing novel digitally-mediated interactions rooted in materiality.

The case study conducted on pop-up and movable books serves as a demonstration of the framework's utility, shedding light on how participants of varying ages engage with and interpret these artefacts. Our findings suggest broader implications for both the HCI community and the CH domain. This research introduces an open-ended approach to support how materials experience can be implemented in CH contexts. The implementation has the potential to find resonance across diverse CH applications and possibly beyond to other augmented experiences featuring substantial material interactions.

Evaluation of the developed XR prototypes with users in a real-life context would serve to validate the utility of experiential material characterisation for designing engaging and meaningful experiences in the context CH-HCI. Such a study will pave the way for further validation and extension of this approach to other (CH) contexts and to the development of a framework and tools to support designers in the creative process of designing engaging and meaningful CH experiences, inspired by and rooted in artefacts' material experiences.

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