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Emily Groves
EPFL+ECAL Lab, Switzerland

Romain Talou
EPFL+ECAL Lab, Switzerland

Andrea Schneider
EPFL+ECAL Lab, Switzerland

Nicolas Henchoz
EPFL+ECAL Lab, Switzerland

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Storing cultural archives in synthetic DNA: An integrated prospective design investigation

Emily Groves*, Romain Talou, Andrea Schneider, Nicolas Henchoz
EPFL+ECAL Lab, École Polytechnique Fédérale de Lausanne, Switzerland
*corresponding e-mail: emily.groves@epfl.ch
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Abstract: As cultural institutions digitize their archives, they become more accessible and versatile. However, there are significant economic and environmental costs to maintaining large databases over time. Synthetic DNA is an emerging technology that can store data at high density, with almost no energy, for thousands of years. Yet, as technical advances bring DNA storage closer to everyday use, little has been done to understand how we will interact with the technology and accept it into society. We developed an integrated prospective design approach to investigate these challenges. This included participative workshops, narrative building and the design of three tangible DNA storage objects. User evaluations showed how summarized information within the object strengthens understanding and appreciation of the technology. We also gathered insights around material and societal perception. This work opens perspectives for the adoption of long-term sustainable preservation for cultural archives, and pushes prospective design methodologies into far-future contexts.

Keywords: prospective design; synthetic dna; data storage; cultural heritage

1. Introduction

We will never know the cultural significance of paleolithic Venus sculptures or what music sounded like before medieval notation. Nor do we have accurate records of the dialogues of Socrates or the writings of Confucius. As content and attributions are still debated today, preserving cultural heritage over thousand years remains highly important. How then can we safeguard the likes of Nelson Mandela's speeches, Picasso's paintings and Wagner's operas for far future generations?

In an effort to both protect and share valuable content, cultural institutions are digitizing their physical archives. This amounts to large volumes of data; for example, INA, the French National Audiovisual institute, claims to store more than 22 million hours of TV and radio recordings (Dusanter, 2021). And though digital databases of cultural heritage are versatile and accessible, they are unsuitable for long-term preservation. The fact that these large archives are stored on hard disks, solid-state drives and flash technology, implies costs, concerns and risks for the long-term.

Some experts fear that the technological infrastructure of digital archives has a significant likelihood of sudden failure, impacting their security (Dominicé et al., 2020). In addition, the current rate of digital obsolescence implies regular and substantial efforts and costs in upgrading obsolete technologies (Pandey & Kumar, 2020). Finally, today's data centers take up great physical volumes and incur significant environmental impacts from the energy required to keep large quantities of digital data over long periods of time (Pendergrass et al., 2019).

1.1 Synthetic DNA data storage

Synthetic DNA data storage involves converting digital binary code of 0s and 1s into sequences of the nucleotide bases A, C, T and G. The resulting molecules are then stored in small silica spheres (Grass et al., 2015). There are several specificities to this data storage technology. Firstly, the four nucleotide bases allow a high information density. Estimations suggest that the volume of data stored in the world, which added up to around 39,000 exabytes in 2012, could be kept in just under 86 grams of DNA (Church et al., 2012). Secondly, synthetic DNA has a long lifespan and remains readable, even under non-ideal conditions, for around 2000 years (Grass et al., 2015). In addition, it requires almost no energy to be maintained (Goldman et al., 2013). It has also been argued that synthetic DNA has a low likelihood of becoming obsolete during human existence given the interest in understanding how to read human DNA (Church et al., 2012).

For these reasons, a handful of projects are exploring the idea of using synthetic DNA to preserve cultural heritage. In 2017, two songs recorded at the Montreux Jazz Festival were encoded and stored in synthetic DNA (Barraud, 2017). More recently, The National Film and Sound Archive of Australia and the Olympic Foundation for Culture and Heritage encoded the first moving image for archival purposes into synthetic DNA (Nicholson, 2020). Simultaneously, technical work on synthetic DNA storage systems seeks to optimize stability (Matange et al., 2021), maximize efficiency (Schouhamer Immink & Cai, 2018) and reduce error (Grass et al., 2015) bringing the technology closer and closer to everyday use.

Despite these developments, we have not found work that seeks to understand how we will interact with this new data technology. How can the tiny silica spheres of DNA be handled outside of the laboratory? What supports are required to communicate what it is, what it contains, and how it should be used? Addressing these issues requires an understanding of human perception of the technology now and in the far future.

1.2 Prospective design

Prospective design methodologies have been developed to anticipate and design for future scenarios (Engeler, 2017; Galdon et al., 2019). They are often based around interactions between a designed intervention and the public. Here we distinctly look at methods that seek to design for the future, as opposed to other speculative design methods, which are more intended to spark debate and reflections on the present (Dunne & Raby, 2013).

Design fiction, which emerged in the mid-2000s (Sterling, 2005), continues to attract interest as a method of researching the future through design (Kymäläinen, 2016; Sharma et al., 2021; Stead et al., 2018). The approach is based on the creation of tangible artefacts that act as an instrument for imaginative study (De Smet & Janssens, 2016). These are artefacts that are relatively quick and easy to create, and which often make reference to popular culture (Brown et al., 2016; *Futures Capsules — Extrapolation Factory*, n.d.). Alongside this, a narrative should be communicated to the audience to provide a context in which the object is supposed to exist (Biggs, 2002). This also helps the object be considered as something "real" which is actually used (Kirby, 2010).

In order to effectively combine the object and narrative, the audience should not be considered as a spectator, but instead an actor in the process. The use of probing to understand the audience's experience can act as an activator of the participatory framework (Sanders & Stappers, 2014). In addition, it can generate unexpected insights around a broad subject area (Gaver et al., 1999). Indeed, when participants interact with a prospective design and answer questionnaires, the aim is to put an emphasis on "weak signals" which may only be mentioned a few times but can open the scope of further work or change the perspective of the design team (Nova, 2014).

1.3 Design research through high-fidelity prototyping

The EPFL+ECAL Lab employs a methodology that combines creative design propositions with in-context, user evaluations. This involves high-fidelity prototypes which have the aesthetic, tangibility and experience of a full "product", but are made in-house by a team of designers and engineers. They are created to challenge a hypothesis during evaluations and to be perceived by participants as credible pieces.

Evaluations, led by user experience psychologists, most often occur in contexts relevant to the project with the aim of maximizing the accuracy of results on human perception. A specific protocol is set for each project including tasks, questionnaires and interviews.

The final outcome is the generation of academic and design knowledge which can be published and shared with the wider design research community (e.g., Henchoz et al., 2021; Ribes et al., 2021). Some prototypes are also implemented as installations or transferred to companies for development for market.

2. An integrated approach

We launched an exploratory project to understand future interactions with synthetic DNA data storage. Based around the design of a storage object, we combined methods from prospective design and design research through high-fidelity prototyping.

2.1 Probing workshops

At the beginning of the project, we ran two workshops, each with 6 participants of varying ages, to gather initial insights and weak signals into perceptions around the use and understanding of long-term data storage media. We compared synthetic DNA with two other long-term storage technologies in order to evaluate participant perceptions of different characteristics. The first is “nano-engraving” which has a significantly lower information density than synthetic DNA, but content can be perceived on its surface and is readable with a microscope (Fuxi & Yang, 2015). It has been used on projects such as a time capsule on the SpaceIL Beresheet Lunar Lander (Spivak, 2019). The second is called “eternal 5D data storage” and involves laser-writing on glass. This has a longer life-span than synthetic DNA, and requires a sophisticated machine to read the data (Zhang et al., 2016). In addition, we wanted to get a better understanding of the kind of content that participants would find pertinent to store for the very long term.

Taking inspiration from design fiction, we prepared three low-fidelity artefacts, each a tangible representation of one of the three technologies mentioned above. To support the narrative, we also made an explanatory booklet, in the style of a commercial leaflet. This presented information about the technologies’ characteristics in simple language with diagrams (Figure 1).

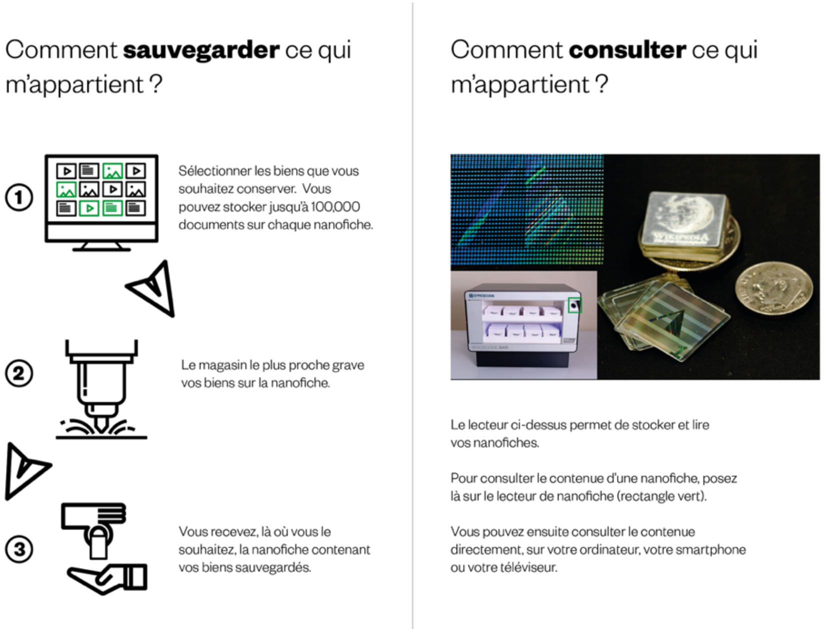

Figure 1. Two pages from the booklet for nano-engraving technology explaining how to save and consult personal data

The workshop was presented to participants in the context of a design research project for the development of a new long-term storage technology. During the workshop we gave the artefacts and leaflets to the participants, along with question cards designed to stimulate discussion (Figure 2). In a participatory fashion, individuals were asked to answer questions on the cards and then discuss them with the other participants.

Figure 2. Participants interacting with low-fidelity prototypes, leaflets and question cards during one of the workshops.

We made several observations based on the discussions between participants. Firstly, we noticed that many found it difficult to believe that synthetic DNA was a credible storage technology compared with nano-engraving and eternal 5D data storage. Participants explained that this was because, unlike the other two technologies, the tangible and relatable notion of engraving or writing is not evident. The idea of a "summary" of content to accompany the synthetic DNA silica glass ball was brought up by participants as a way to facilitate this understanding. We also observed that participants did not find it relevant to store personal data (such as documents and photos) over the long term, as they thought that their content would not interest far-future generations. In contrast, participants could see value in storing institutional or cultural heritage over the long term, as it has a wider public interest and is usually subject to curation.

2.2 Design influences

Following the workshop, we investigated several aspects in more detail to frame the design of the synthetic DNA storage object.

Firstly, we looked at how the object could communicate what it is and what it contains. In our workshops, participants suggested adding a “content summary” to facilitate understanding of the content of synthetic DNA. The idea was to add another, directly consultable, medium to communicate a summary of what is held on the synthetic DNA. In this way, the content summary acts like the blurb of a book, or a track list on a record sleeve.

As the synthetic DNA can last thousands of years, this communication also has to stand the test of time. Reports of the Waste Isolation Plant Project, which investigated how to communicate the danger of nuclear waste into the far future, suggests that using a combination of media, as well as a variety of iconic, symbolic and linguistic signs increases the chance of information being understood over the long term (Good & Hendryx-Parker, 2006; Rechard, 2000). We were also influenced by graphic principles of Sébasitian Noguera who highlights the importance of parsigraphy (writing systems where each symbol represents a concept) for long-term communication (Noguera,2020).

Similarly, the interactions and materials would have to last over the long term. We looked at The Clock of the Long Now, a clock designed to keep time for 10,000 years (Hillis et al., 2011). This describes the need for a long-term design to be independent of any external device apart from human manipulation and natural conditions. We also consulted with materials scientists to discuss credibility of different material propositions, where hard metals, glass and minerals were suggested as long-lasting.

Regarding the object form, we sought to produce a simple geometric and solid shape to enhance the object recognition in various conditions (Pasupathy et al., 2018) which might occur over millennia, as well as the perception of a man-made object (Good & Hendryx-Parker, 2006). More generally, we considered the idea that creating an emotional relationship with an object can motivate people to value and preserve it (Chapman, 2012; Norman, 2004).

In light of comments made by participants during the probing workshops, we decided to focus on cultural heritage content. We chose to work with two well-known heritages; the audiovisual archives of the Montreux Jazz Festival and the document-based collection of the Swiss Literary Archives. These represent two very different types of archives which would help to explore the impact this has on the design and people’s perception.

These references led us towards designing an object that both stores synthetic DNA, and has a content summary which could be read without using any external technology. We were inspired by mid-17th century microscopes which functioned with just natural light and mirrors. These were cylindrical objects with rotating slide trays used to view different media. This brought us to the concept of a nano-engraved disc, replicating the form of a slide tray, which could be rotated to show different “pages” of summary content related to the archive.

2.3 Design process

We collaborated with a micro- and nano-technology lab at École polytechnique fédérale de Lausanne (EPFL) to create the discs for our prototypes with photolithography, a technique mimicking the results of the more expensive micro- and nano-engraving on nickel plates. The standard size of the glass plate for photolithography (127×127 millimeters) defined the diameter of the object. We developed several tests to work out the scale of text that could be readable with the microscope lens and compatible with photolithography. The focal length also determined the height of the object (Figure 3).

Figure 3. Tests to determine the focal length for the integrated microscope.

The pages of the final discs show archival text (in multiple languages), images and information about synthetic DNA storage (Figure 4). The content was selected in partnership with the institutions in charge of the two heritages.

Figure 4. Three "pages" of summary content. Information on how to use the object (right), Swiss Literary Archive content (middle), Montreux Jazz content (left).

We decided to make the object out of milled aluminum, which has a credible longevity and durability and allowed an accurate turning mechanism. The black coating was chosen to highlight engravings on the surface (Figure 5). These engravings, also in multiple languages, served to give an initial explanation of the content held within the object.

Figure 5. Engravings on the surface of the smallest prototype in several different languages and scripts. Photography: Daniela & Tonatiuh / EPFL+ECAL Lab

We made three different synthetic DNA storage objects (Figure 6), each with a different quantity of summary content. The amount of summary content also corresponds to the size of the object.

Figure 6. The three synthetic DNA storage object prototypes. On the left, the medium-sized prototype in the middle, the largest prototype, both with integrated microscopes with an eyepiece on the top surface. On the right, the smallest prototype with no content summary. Photography: Daniela & Tonatiuh / EPFL+ECAL Lab

The smallest object, the control, has no content summary whilst the two larger objects have engraved content summary discs (Figure 7). On all three objects, the central section can be removed from the object by hand to reveal a glass ball, representing a silica sphere to hold synthetic DNA. For the two larger prototypes, this central part also houses the content summary disc, and can be turned by the viewer from the outside of the object to browse through the pages of content. The medium-sized prototype has a micro-engraved summary disc of 19 pages viewable via a microscope integrated into the object. The largest prototype has a longer, nano-engraved, content summary disc of 77 pages with a more powerful lens.

Figure 7. The summary disc of the medium-sized prototype with circular "pages" of content and the glass ball for housing synthetic-DNA in the top left of the disc. Calibration marks are engraved on the outer surface to index the content. Photography: Daniela & Tonatiuh / EPFL+ECAL Lab

To help participants in our evaluations imagine different roles, placements and aesthetics for the object, we also designed an interactive digital platform. Presented in a manner similar to a sales platform, it uses 3D renderings to place the object in different contexts, such as at home or in a museum (Figure 7). We also used it to explore the aesthetics of materials other than the black metal chosen for the physical prototypes; this included a series of other metal finishes, ceramics, minerals and composites.

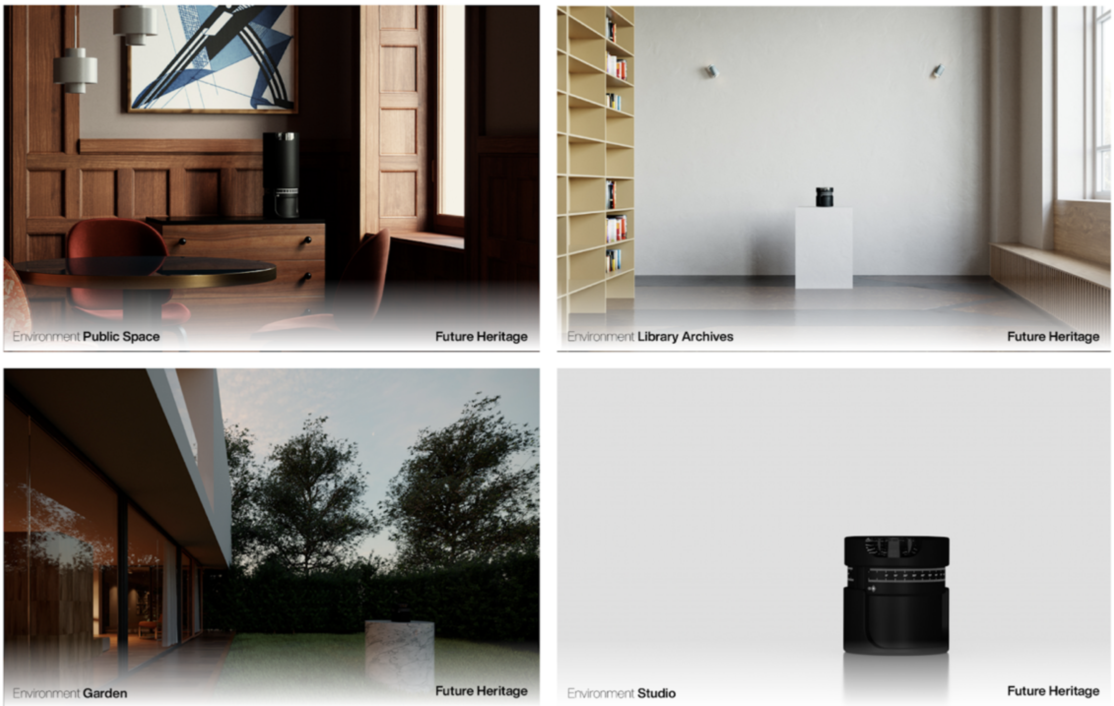

Figure 7. Screenshots from the interactive platform showing the object in different contexts.

3. User evaluations

3.1 Objectives

The user evaluations had three objectives.

- To test whether the idea of the "content summary" would facilitate the understanding and acceptance of synthetic DNA storage.
- To engage participants in debate around the perception and role of such an object in society.
- To understand whether the type of archival content, or somebody's personal relationship to the content influenced the first two objectives.

3.2 Participants

We recruited 39 participants ranging from 19 to 76 years old, with a mean age of 46 (SD=13). 10 participants were recruited for their link to the Swiss Literary Archive. 10 participants were recruited for their link to the Montreux Jazz Festival. We define these two categories as “experts”. The remaining participants were recruited with an aim of having a link to archives or cultural heritage in general. 22 of the 39 participants were categorized as archivists.

3.3 Study design

In a between-subjects study design, half of the participants interacted with largest prototype followed by the smallest, and the other half with medium-sized prototype followed by the smallest.

Three different locations were used to conduct the tests. Each one was chosen to contextualize the archive in question and reinforce the narrative. For the Montreux Jazz content, participants did the evaluation in two locations dedicated to the festival archive. For the Swiss Literary Archive, a library setting was chosen.

The user test protocol was granted ethical approval by the Human Research Ethics Committee of EPFL (reference 085-2020 / 30.11.2020).

3.4 Protocol

There were four parts to the 60-minute testing session. In the first part of the test, participants were invited to interact with the first object (the largest or medium-sized), and to imagine that they worked as an archivist and had received this new device, but had not been told how to use it. They were asked to try and understand what it was and how it worked. After a short time, the facilitator orally asked the following questions:

1. What object do you think you have in front of you?
2. What kind of information do you think this object contains?

The facilitator then asked the participant to complete several tasks related to the summary content:

1. Go to [section dependent on archival content] and tell me what you see
2. If you wanted to show this content to your friends later using your smartphone, how would you do it?
3. Go to the end of the content and tell me what you see
4. Remove the disc. Can you describe what you are holding in your hands?

After these interactions, the participant filled out a questionnaire relating to the first object.

In the second part, participants were invited to interact with the smallest object. They were given the same scenario and asked the same questions as in the first part, but there were no tasks as there is no summary content. After these interactions, the participant filled out a questionnaire relating to the second object.

For both part one and two, the questionnaires were designed to evaluate several aspects of the objects. This included the pertinence of the object now and in the future. We also asked questions about the presentation of the content and the participant's impressions of the different qualities of the object. Likert scales of 1-7 were always used with an extra line given to record qualitative explanations for the response. We included the short and widely used "User Experience Questionnaire". Both classical usability aspects (efficiency, perspicuity, dependability) and user experience aspects (originality, stimulation) were measured. We also asked the participants to quantify their relationship to the archive.

In the third part of the session, participants were asked to interact with the digital platform. Whilst doing this, the facilitator orally asked and noted responses to a questionnaire. This covered questions on material choices of the object. It also asked questions about the participant's perception of the status the object should take in its environment, exiting outside, in a public space or in a closed archive.

The final part of the test consisted of an oral semi-structured interview between the participant and the facilitator. This asked for specific impressions from the session such as their preferred object, what could be improved, and what influenced their decision to earlier questions.

3.2 Results

In both conditions, the prototypes with a content summary were preferred compared to the smallest, DNA only prototype. In the condition with the small and medium prototypes, 42% preferred the small, 47% the medium and 11% did not have a preference. In the condition with the small and large prototypes, 65% preferred the largest, 30% the small and 5% had no preference. The presence of the summary content was favored for several reasons stated in qualitative feedback. Firstly, because it gave an insight into the type of content within the object. Participants specified that this gives accessibility to an audience beyond laboratory technicians and helped them understand the concept of synthetic DNA storage. Secondly, because it allows the object to be a stand-alone device without the obligation of another reading tool "[The fact that it is]… self-sufficient is very interesting in the face of the programmed obsolescence that prevails today".

During the interviews, we also asked participants whether they thought the objects would be pertinent in 50 years and in 2000 years. Overall, the pertinence today was rated as 4.50 out of 7 (SD = 1.74, 1 = completely disagree, 7 = completely agree), pertinence for audiences in 50 years was rated as 4.95 (SD = 1.74) and in 2000 years as 5.07 (SD = 2.12).However, there were also some differences in opinion. For example, archivists perceived the smallest object as being less pertinent today (M = 2.91, SD = 1.44) compared with non-archivists (M = 4.19, SD =1.64)), $F(1,32)$= 3.02, p = .09. Also, participants interacting with the Montreux Jazz content rated the pertinence of the smallest object in 50 years to be higher (M = 4.37, SD =1.77) than participants with the Swiss Literary Archive content (M = 3.63, SD = 1.98),

$F(1,32) = 3.097$, $p = .088$. What's more, in all cases, there was a significant difference between "pertinence for someone who knows the heritage" ($M = 5.56$, $SD = 1.32$) and "pertinence for someone who does not know the heritage" ($M = 3.84$, $SD = 1.61$, $F(1,74) = 35.24$, $p < .001$).

After interacting with the prototypes, we asked participants about their perception of certain physical qualities. Firstly, the objects were rated as very aesthetic ($M = 6.23$, $SD = 0.66$, 1 = not aesthetic at all, 7 = very aesthetic). Secondly, the robustness of the objects was rated as high ($M = 5.72$, SD = 1.23, 1 = not robust at all, 7 = very robust). Other qualitative statements revealed that participants thought that the object's significant weight (between 6 and 11kg), gave it "a more prominent status". The level of expertise, being a professional archivist and the archive type did not influence these perceptions.

From the visualizations given on the interactive platform, the preferred material was metal with a mean score of 5.62 out of 7 ($SD = 1.87$), compared to ceramic ($M = 4.46$, $SD = 1.72$), minerals ($M = 4.19$, $SD = 1.82$) and terrazzo ($M = 3.00$, $SD = 1.74$). Metal was perceived as having few links to social class and for being timeless. However, 28% of the participants expressed an interest in the use of transparent materials, "it allows you to see the heart of the object, to perceive the content more immediately".

In terms of its place in society, the object was perceived more as a functional tool (scoring a mean of 5.39 out of 7 ($SD = 1.69$)) rather than an ornamental object ($M = 4.11$, $SD = 1.98$). In addition, in the qualitative interviews, the role of the object was divided into two categories by 72% of archivists: protect and preserve versus spreading knowledge to the widest audience.

During all evaluation sessions, only 3 of the 39 participants expressed doubts about the credibility of the artefacts to the point of disrupting their involvement in the role-play. Similarly, the interactive digital platform was perceived as familiar by the participants, matching expectations with a prospective methodology.

4. Discussion

4.1 The impact of the content summary

The storage of data on synthetic DNA is a new and seemingly abstract technology, for which interactions and perceptions have yet to be explored. Our hypothesis during this project was that by presenting a detailed content summary alongside the synthetic DNA, it could be made more tangible, understandable and accepted.

We tested this by developing a series of prototypes containing cultural archival material with nano-engraved content summaries. Our results showed that this summary indeed helps understanding, particularly when shown in more detail (around 90 pages). Participants in our evaluations also perceived the prototypes as aesthetic, robust and significant. As cited in the literature, this emotionally positive perception, of both the summary and the object itself, is considered important for promoting its perpetuation by future generations.

4.2 Reflections and developments for future DNA data storage objects

This work makes some first steps towards understanding the societal acceptance of synthetic DNA data storage. However, it also opens up many avenues for further exploration.

Interestingly, we did not observe strong opinions from archivists regarding the impact it this technology could have on their profession. This could be due to the fact that it still appeared too far removed from their daily interactions with archives. However, archivists did point out a duality in the role of the object. The first is its duty to protect a heritage and the seconds is its capacity to spread knowledge or experience to the widest audience. This produces a potential conflict in scenario of use between being hidden and exposed which should be explored further.

We also did not observe marked differences in perception related to the type of archival material despite audiovisual and literary content being very different. This may be due to the fact that in both cases the content was limited to small black and white images and text. Therefore, we think that the experience with the archival content, namely through the content summary, could also be developed in future work to make it more meaningful and specific to the archive in question. Enhancing the emotional connection with the object in this way could increase its acceptance and longevity, as mentioned previously.

The size and the materiality of the object, which are the results of technical and perceptual considerations, could be seen as a contradiction with the high density and low energy use of DNA data storage. However, as the artefact size remains fixed, even massive archives could be stored in a single object which remains very small compared with traditional storage techniques. In addition, the energy required to manufacture such an object is several orders of magnitude less than maintenance on traditional supports. Finally, the size and the materiality impact the status of the object, fostering an attitude of preservation. This could reduce the need to multiply copies and to manufacture other layers of protection.

4.3 Integrated prospective design method for far-future scenarios

The majority of prospective design research deals with future scenarios in 5, 10 or maybe 50 years. In contrast, our approach looked up to 2000 years into the future, requiring a large degree of forward-thinking by the participants.

To address this, we combined methods from prospective design with high-fidelity prototyping and user evaluations. Early in the project, probing workshops allowed us to engage in debate with participants about an unfamiliar subject and gather weak signals to inform the design direction. Later on, the high-fidelity prototypes allowed us to investigate tangible interactions and experience with the heritage content. We think that by engaging in hands-on tasks with a physical object that has tactility, weight and mechanisms, participants were able to give us insights beyond what would be possible with a low-fidelity prototype typically used in such projects. Indeed, only 7.7% of participants questioned the object's credibility.

Although we were able to achieve high credibility, our methods could be developed to aid projection into future scenarios. For example, we saw some surprising outcomes from the final evaluations, notably that we did not observe significant influences of the type of archive or of the participant's profession on our results. The evaluation protocol was largely based on a typical user experience evaluation in the style of questions asked and the duration (one hour). We think that a longer format could allow for a more in-depth introduction of the subject, and would give the opportunity to question different future scenarios (such as Jim Dator's Alternative Future archetype (Dator, 2019)). Looking towards other disciplines, such as applying far-future horizons to the Foresight Methods Combination Matrix (Popper, 2008), could allow us to identify potential integrations to strengthen our approach.

Similarly, in the initial workshops, participants stated that they could not see the interest in storing personal data far into the future. This led us to work with cultural archives which were suggested as having a wider relevance. However, an alternative strategy could instead be to ask participants today to look back into the past, allowing them to experience both cultural and personal data of their ancestors. This strategy could produce very different outcomes, and allow participants to understand the scales of time in a different way.

5. Conclusion

We proposed an object to preserve cultural heritage over millennia. By implementing a methodology combining prospective design with high-fidelity prototyping and contextualized user evaluations, the project gives insights into the potential interactions and perceptions of synthetic DNA data storage. The work opens perspectives for the adoption of this new technology by cultural institutions, presenting a secure, dense and low-energy way of preserving heritage over thousands of years. The combined methodological approach offers a new outlook for understanding the perception of technologies with far-future horizons.

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About the Authors:

Emily Groves is a design researcher and educator. With a background in anthropology, experience design, and inclusive design, her interests lie at the intersection of technology and culture.

Romain Talou is a design researcher and product designer. With a background in graphic, media and interaction design, his multi-support practice focuses on the use of fast prototyping.

Andrea Schneider is a user experience researcher with a background in cognitive psychology. She is interested in researching the interaction between humans, technology and design.

Nicolas Henchoz is the founding director of the EPFL+ECAL Lab which explores the perspectives of emergent technologies through design. Trained as a scientist, he previously worked in science journalism and at the direction of the Ecole Polytechnique Fédérale de Lausanne.