Non-Manhattan Approximate Nearest-Neighbour and Maximum Empty Cube

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Abstract

Haptic perception is commonly prohibited when experiencing museum artefacts. This inevitably results an incomplete experience for the visually impaired (VI) as the tactile exploration of an object is a dominant substitute of sight. In this paper, we focus on the utilisation of ICT to foster social inclusion and enable cultural heritage content to become more accessible to VI both physically as well as intellectually. The production of haptic accessible replicas is highly related with cost-effectiveness. Thus, we developed three prototype low-cost systems that are based on the *smart exhibit* concept that involves features that are common in Internet of Things devices such as single board computers, microcontrollers, rfID and proximity sensors along with on-demand narrrtion and 3D digitisation and printing. We present *aptos.Exhibit*: a multi-user smart exhibition platform, *aptos.Map*: a stand-alone interactive tactile map and *aptos.myExhibit*: a 3D printed miniarures based museum-kit to enable museum reserve exploration after the completion of an actual visit. We describe in detail the functionality of each prototype and discuss on their implementation properties. The cultural content delivered through the three prototypes is derived from our previous monument 3D digitisation projects in Northern Greece. An evaluation session where VI users experienced all three systems was implemented and we collected their responds through an interview-based questionnaire. We present in detail the performance results related to usability, comprehension of the cultural and historical background being encapsulated. Again, we discuss on the various results and indicators towards the proposed solutions and discuss further on our findings related to the haptic access of cultural heritage reserve and the on-demand narration.

Keywords: museum, visual impairment, 3D printing, 3D digitisation, tactile museum exhibit, Internet of things, recorded narration, human-computer interaction

1. Introduction

During the last decade, numerous actions focused on the decrease of cultural exclusion and enhancement of the society participation sense of the visually impaired (VI) have taken place. Many of them are based on European Union policies and commonly involve various public bodies, cultural heritage institutions, VI advocacy groups as well as research institutions [1][2][3][4][5][6][7].

ICT provides a wide range of solutions that contribute in developing systems to allow the physical and intellectual access to the cultural heritage (CH) content offered by museums. The utilisation of tactile exploration and narration are significant features of such systems as they enhance VI museum visit experiences and CH content interpretation. The utilisation of ICT is performed under multidisciplinary approaches in an effort to allow apart from the systems' efficient development and content delivery, their objective evaluation, future evolution and standardisation.

The work presented in this paper is part of the APTOS project [8] which is focused on the development of experimental VI-oriented low-cost systems that enable the appreciation and understanding of CH content by utilising tactile exploration and on-demand narration. These features are significant substitutes for sight while the latter may also contribute in enriching sighted people museum visits. The three experimental systems that are presented in this work may be exploited during a museum visit (aptos.Exhibit, aptos.Map) or after it (aptos.myExhibit). More specifically, their implementation is based on the functional and non-functional properties of the smart exhibit (SE) concept, we have defined in a previous work [9]. The systems rely on features that are usually found in Internet of Things devices such as WiFi connectivity, single board computers or microcontrollers, rfID tagging, on-demand triggering and proximity sensors.

Furthermore, the proposed systems deliver CH content through 3D digitisation and printing technologies along with on-demand point-of-interest based narration. A number of monuments, located in Northern Greece, were used as the CH content that is delivered through the prototypes. These monuments have been previously 3D digitised within the frameworks of EU and nationally funded projects [10][11]. We have objectively evaluated the systems' performance by organising a number of trials that involved VI users.

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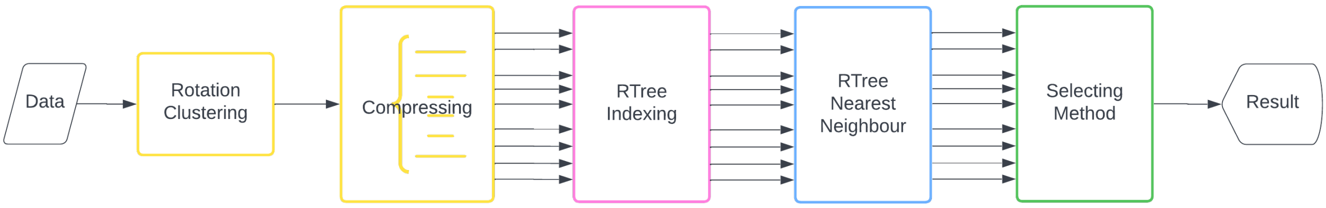


Figure 1: Main block diagram of methodology.

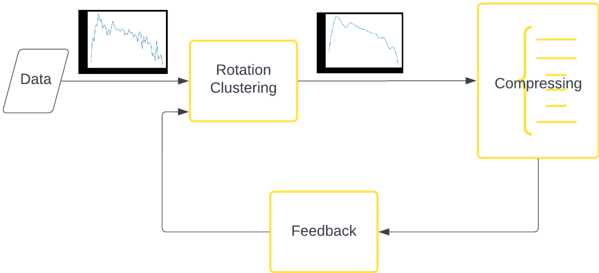


Figure 2: Rotation clustering and compressing.

2. Rotation clustering and compressing

In order to create spaces with objects that are relative Manhattan, we cluster the data by their relative rotation. Since we have one-dimensional clustering and random distributions, we choose to use kernel density estimation. The pdf can be derived as follows:

$$p(x) = \lim_{n \to \infty} p_n(x)$$

where $p_n(x)$ is equal to:

$$p_n(x) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{V_n}\phi\left(\frac{x-x_i}{h_n}\right) = \frac{1}{n}\sum_{i=1}^{n}\delta_n(x-x_i),$$

$$\delta_n(x) = \frac{1}{V_n}\phi\left(\frac{x}{h_n}\right)$$

For ϕ the following holds true:

$$\phi(x) \geq 0 \textbf{ and } \int_x \phi(x)\,dx = 1$$

Here, we choose ϕ to be equal to a gaussian distribution:

$$\phi\left(\frac{x-xi}{h_n}\right) = \frac{1}{h_n\sqrt{2\pi}}\epsilon^{-0.5\left(\frac{x-x_i}{h_n}\right)^2}$$

h_n is equal to bandwidth and the variance of the gaussian distribution.

2.1. Bandwidth selection

The choice of bandwidth is crucial to the kernel density estimation. If the window is small or large, the curve produced may be undersmoothed, or oversmoothed respectively. Many methods where tested, such as rule of thumb, since our data are univariate and the density function is Gaussian, with bw being set equal to:

$$bw \approx 0.9\min(\hat{\sigma}, ICQ/1.34)n^{-1/5}$$

The Suleiman's rule of thumb, was discarded because the distribution is a sum of normal distributions. The second choice was to create a cost function and minimize it. We define The cost as:

$$J_m(x) = \sum_{cl=1}^{N_{cl}}\left(\sum_{i=1}^{N_g}\left(\frac{1}{n}\sum_{j=1}^{n_e \in i}\left(x_j^i\right)^m\right)^{\frac{1}{m}} \cdot w_{i,cl}\right.$$

$$\left. - \left(\frac{1}{n}\sum_{j=1}^{n_e \in \max(w_{i,cl})}\left(x_j^i\right)^m\right)^{\frac{1}{m}} \cdot \max(w_{i,cl})\right)$$

The apply Newton's relaxed method of optimization.

$$bw_{k+1} = bw_k - \eta\frac{J^{(1)}(bw_k)}{J^{(2)}(bw_k)}$$

The derivatives are calculated with finite differences:

$$J^{(1)}(bw_k) \approx \frac{J(bw_k+s)-J(bw)}{bw_k} = \frac{1}{bw_k}\left(J(bw_k+s)-J(bw)\right)$$

$$J^{(2)}(bw_k) \approx \frac{J^{(1)}(bw_k+s)-J^{(1)}(bw)}{bw_k} =$$

$$\frac{1}{bw_k^2}\left(J(bw_k+2s)-2J(bw_k+s)+J(bw_k)\right)$$

The method that seems to produce the best results is done by remodeling the cost function as:

$$J_{new}(bw) = |J_{norm}(bw) - w_{Ncl}J_{Ncl,norm}(bw)|$$

Here the old cost is normalized and reduced by a weighted normalized cluster cost. The w_{Ncl} is a hyper-parameter. This function produces a list of J values with indexes that point to a list if bw. We then can find the minimum cost corresponding bw for each cluster and choose the biggest bw, since it minimized

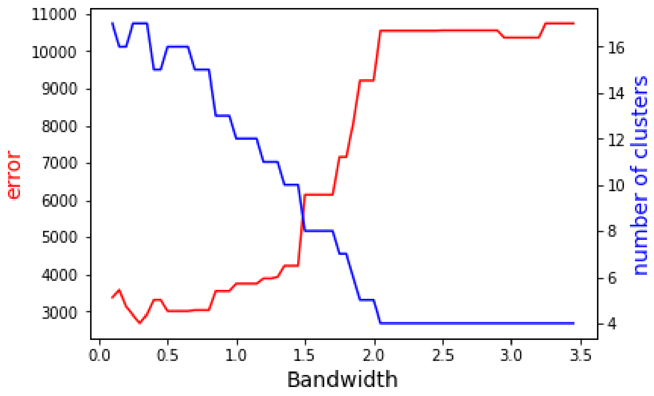


Figure 3: Cost function and cost function for number of clusters per bw.

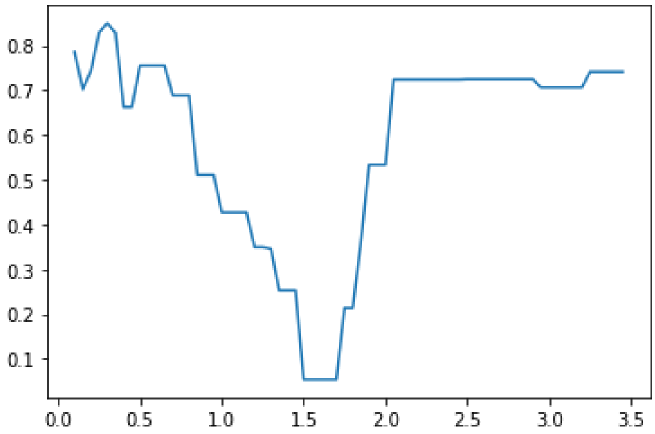


Figure 4: New cost function for $w_{cl} = 1.5$.

the number of clusters. This has to be done for a field of bw values.

$$\max\left(\sum_{w_{cl}=w_0}^{w_n} \min J_n(bw, w_{cl})\right) = \max[bw_0, bw_1, \ldots, bw_N]$$

$$bw_N = bw_{opt}$$

2.2. Compression

The clusters produced by the process have a mean and a max value. The difference is related to the fact that each cluster is a weighted sum of the gaussians, each one contributing by a factor. We choose to compress each value of a cluster to each mean and not max, since the mean is represents the data more accurately than max, which is the mean of the gaussian with the most contribution.

$$C_i(j) = \delta(x - x_{m_i})R_{m_i} \forall i, j$$

3. RTree indexing

Our methodology involved the collection and analysis of users' requirements for the APTOS project prototype systems. The three primary prototypes will include: *i)* a group of SEs composing a museum exhibition, *ii)* a table-sized tactile map for understanding a museum's layout and *iii)* post-visit museum-kits. To capture the appropriate information, we created an extensive questionnaire and a haptic performance assessment object. Each one aims at acquiring different while complementary feedback. The first is focused on capturing insights and preferences from VI-cultural reserve interaction experiences (linked to SE functionality), while the second attempts to objectively quantify the performance of VI and non-VI people on completing various haptic tasks. In the following sections, we analyse in detail both methods and their implementation.

3.1. Specifications questionnaire

A five-part online questionnaire was created to examine the requirements of VI people when it comes to visiting museums, galleries, etc. and their acquaintance with technological tools that enhance accessibility. This survey aimed at outlining the opinions and attitudes of the respondents towards the specific exploitation of 3D printing and audio narration in such spaces, in order to create a multi-sensory experience.

The 1^{st} group of questions is focused on demographic information, visual impairment, level of education and braille knowledge of the respondents. The goal of these questions was to portray the users to whom these applications would refer to. The 2^{nd} group involved questions about visits in museums and other cultural heritage spaces and the respondents' knowledge of accessibility tools found in such places. These questions aimed to define the status quo in such spaces, regarding the existing museological approaches and possible tools and projects developed in order to give access to VI people, not just when it comes to their physical access, but also regarding their intellectual access to the exhibits and the exhibition as a whole. Another aim of the questions was to define their desired type of visit in such places (e.g. guided, independent, as part of a larger group of visitors, etc.). The 3^{rd} group focuses on questions regarding the use of recorded narrations as a tool of accessibility and information in spaces of cultural heritage, their exhibits and the "stories" that these include. Important aspects of the interaction between a user and a SE are attempted to be addressed by this group. Respondents are asked to quantify narration properties such as duration (e.g. single long narration, multiple short independent narrations), sound quality, clear articulation, voice timber, narration speed and style. Furthermore, they were asked to rate specific SE properties in relation to narration control (e.g. pause/continue, restart narration session, fast forward or backward 10 seconds, skip to previous or to the next narration session, etc). As this group is highly related to specific range of SE properties, it attempts to gather opinions about event monitoring and triggering, narration content and control. The questions of the last two groups were designed to examine respondents' contact with 3D replicas of artefacts (4^{th} group) as well as their perception of smart 3D replicas of exhibits (even at a conceptual

Figure 5: Various moments during the response collection of the questionnaire and the haptic performance assessment before and during the implementation of SARS-CoV-2 infection control measures.

Figure 6: Perspective projection rendering of the haptic performance assessment 3D model that was designed in Blender. The 3D printed object has a length of 18*cm* and width of 10*cm* and was 3D printed using a low cost fused filament fabrication printer with PLA material.

level) (5^{th} group). They are focused on defining the importance of haptic exploration for VI people, especially when used as a tool to 'see' the artefacts and comprehend their morphological features as well as other elements that are challenging to be described verbally. The specifications questionnaire can be found online [12].

3.2. *Haptic performance assessment*

Enabling the tactile exploration of 3D printed objects is a process that should take into account a number of parameters related to the morphological characteristics of surface elements, their dimensions, spatial density, shape complexity, etc. To determine and fine tune the 3D printing properties for the fabrication of our three prototypes, we designed a haptic performance assessment object that was explored by VI and non-VI groups. The object was designed and printed using open source tools (Blender 3D modelling tool [13], Cura slicing application [14]). Three replicas (Figure 5) were produced using a low cost Fused Filament Fabrication (FFF) 3D printer with PLA material and a 0.1*mm* Z-axis layer increment. It should be noted that FFF printers have a dimensional tolerance of ±0.15% and a lower limit of ±0.2*mm* due to their operational approach (heated thermoplastic extrusion followed by quick cool-downs results wrapping and variations). The size of the object attempts to approximate the size of a compact tablet computer (Figure 6). Initial 3D printing settings included a *0.1mm* Z-axis layer increment and a 20% infill density, which resulted a total of 12 hours printing time and almost 24*m* of filament.

In terms of design, the assessment object carries a total of ten different tasks (Figure 7). Each task is composed by 3D geometric shapes and elements that facilitate the evaluation of certain tactile information design practices. Each task is identified by a large triangle that points towards the tactile exploration direction that should be followed. The overall surface design is divided into two main areas. The left half includes six tasks organised in rows, while the right half is populated by four tasks organised in two columns. A smaller triangle indicator is placed at the bottom right corner of the object to help the candidate determine the correct orientation when holding/exploring the object.

More specifically, task one uses gaps of variable size between sequential prisms and is focused on quantifying the minimum distance that can be identified between two discrete points on the surface. This introduces a haptic sensitivity task that follows the paradigm of the standardised two-point discrimination sensory evaluation. With each successive subtest, the two prisms gradually move closer until the stimuli are perceived as one. The smallest distance that can still be perceived with a gap, is measured and treated as a reference to calibrate the density of tactile information.

Task two presents button triggers of different height in a sequential order and attempts to identify the user preferences in relation to its coexistence next to other surface elements. Buttons are quite common functional triggers that most VI people are familiar with and can instantly identify. The goal is to capture what their preference is, when such elements are blended with tactile information instead of being placed in an isolated surface area (i.e., the bottom side of a SE or the corner of a tactile map). This task aims to evaluate the optimal height profile for triggers that elegantly and smoothly disrupt the tactile exploration, to enrich it with contextually relevant experiences (narrative content).

Tasks 3 – 6 have a similar role and are focused on the haptic tracing of embossed routes implemented with different tactile patterns. Each route represents a contrasting level of exploration difficulty, in terms of density and orientation. There is a starting point described by a smooth embossed hemisphere, while the end is indicated by an embossed basic geometric shape that has to be identified. The purpose of these tasks is to evaluate the pattern's suitability for encoding and diversifying tactile information. Solid lines with distinct horizontal and vertical parts may

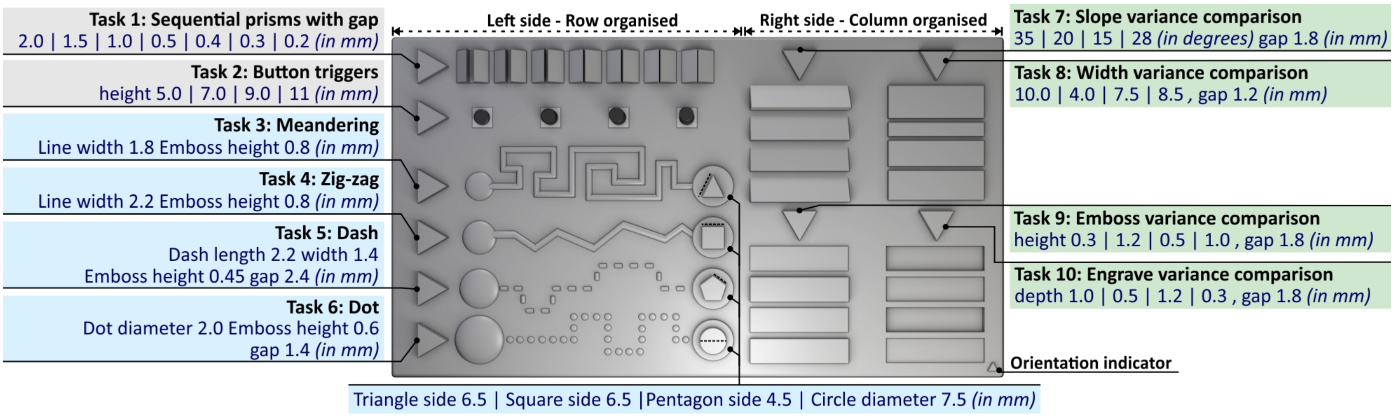


Figure 7: Haptic tasks topology and analysis. Tasks are grouped together based on the specific tactile exploration skills required. Each task is indicated by an embossed triangle. Another smaller triangle at the bottom right side of the object is used for proper orientation.

act as the outline of a domain, shape or space that needs to be easily identified on a tactile surface. Dashed or dotted lines can usually translate information about alternate routes or internal subspaces. Zigzag lines, while able to produce more complex outlines for tactile shapes and spaces, they also challenge haptic memory in terms of orientation and perception. Finally, the ability to swiftly identify primitive shapes contributes in using them as tactile indicators and mapping conventions. The above tasks can provide significant feedback for building a library or a toolbox of tactile design elements and patterns that can effectively annotate and enrich the surface of a SE. The purpose of these annotations is to explain the SE functionality, guide their exploration, aid map orientation, and achieve all these with the minimum tactile noise and a maximum acceptance.

Tasks $7-10$ evaluate comparability of dimensions and other surface features. These tasks require the classification of simple shaped features based on a given property (e.g. slope, size, protrusion, cove). These properties have multiple meanings and roles in encoding tangible information, and its correct haptic interpretation enables an individual to identify and understand details of SE tactile representations. For example, detecting slope can help distinguish an accessibility ramp from an uphill pathway, on a tactile map. Furthermore, the ability to understand subtle size and shape variations, facilitates the perception of scale for the actual exhibits. Aiming to deliver an extensive set of similarly sized 3D replicas that can be effectively handled and explored with ease, the APTOS project will inevitably produce SEs that represent exhibits of significantly different size. Being able to efficiently compute and imagine the actual size by translating different scaling conventions, may significantly enhance the experiencing of exploring an SE. Finally, comparing between embossed or engraved shapes quantifies how haptic memory can track surface layers and capture them as part of the tactile information context. In all of the above tasks, the respondent is encouraged to apply, test and train new palpation techniques that enhance haptic sensitivity and organise haptic memory in various ways.

During each assessment, we have used a secondary questionnaire to collect evaluations for every task's design complexity and haptic challenge. Both VI and non-VI groups answered it, exactly after the completion of each task, offering feedback on how their approach could benefit the design of our prototypes with desired tactile features. This questionnaire is also available online [15].

3.3. *Response collection*

The response collection took place between the various lockdown periods that were applied for the SARS-CoV-2 infection control measures in Greece during 2020 and this affected both the collection times as well as the number of respondents. As for the questionnaire, the majority of the responses were collected in person by the project's team members, in the form of a short interview, where the respondents were encouraged to make further comments related to the content of the questionnaire, their general experiences in visiting museums or other cultural reserve exhibitions, as well as any suggestions for improving the proposed system functionality. A total of *40* VI respondents have completed the questionnaire. Figure 5 holds various moments of the response collection.

For the haptic assessment, multiple 3D prints of the object allowed not only the simultaneous response collection but also the application of the prerequisite surface sanitation procedures. The haptic performance assessment was completed by 30 VI and 53 non-VI respondents (55% men, 45% women). 73% of the VI respondents had congenital visual impairment while the rest acquired it at some point in their life through trauma or a degenerative disease. For the non-VI respondents, we ensured they had no visual access to the 3D printed object neither before nor while performing the test. The results for each group were collected separately and their analysis provided useful insights and lead our conclusions.

4. Results and discussion

The questionnaire and haptic performance assessment play a significant role in acquiring vital information for the design and implementation of the experimental systems. Their goal was to portray the potential APTOS users and to understand how various characteristics can affect different interests, experiences, approaches, use of technology and design choices.

4.1. Specifications questionnaire results and analysis

From the answers of the 1^{st} group of demographic questions, we deduce that a total of 40 people answered the questionnaire (23 men and 17 women, all Greek respondents). The predominant age group is $25 - 44$ years old (47.5% of the respondents). The 1^{st} group of the respondents were completely blind, with the rest being partially visually impaired, while 45% of the respondents had congenital visual impairment the rest became visually impaired at a later point in their lives. Over half of the respondents (52.5%) have received a post-secondary and higher education, while 80% of them can read Braille. Almost all respondents (92.5%) use some sort of technological accessibility application/device in their daily lives.

The 2^{nd} group of questions showed that the respondents visit culture related spaces once per year (50%) or per semester (25%). The majority (71.8%) often faces difficulties when it comes to navigating and exploring an exhibition. Almost all respondents (92.5%) would like to take part in a conventional group tour, with the aid of trained museum staff, but it is not quite common for the employees to be accommodating. A total of 64% of the respondents answered that they have never encountered museum staff educated towards aiding VI people. These questions, while defining the current situation in terms of VI people and their physical and intellectual access to exhibits and exhibitions as a whole, also aimed at defining preferences when visiting such a place that can guide the design and development of the visit and exhibition experience within the APTOS project. The need for staff training and multi-user function appears a necessity.

What stands out from the answers to the 3^{rd} group is the benefits and the characteristics of audio narration as a tool of assistive technology in the hands of VI people. They are usually the only source of information that they have during their individual visits and they are considered an extremely helpful tool by 72.5% of the respondents. Nevertheless, their availability seems to be extremely limited on most occasions. When going into detail about the preferable characteristics of audio narration, 85% of the respondents mostly stated that they would rather choose from several short, recorded narrations than having to hear a single extended one with all various information compiled. Another highlighted response, which will guide the project team in terms of audio content generation and user interaction in terms of narration control, was the importance of sound quality and clear articulation over other narration features such as vocal timbre, speed and style. Again, the importance of giving full control over a narration (ability to pause, restart, skip to the next or previous narration) was significant. Figure 8 holds the respondents preferences for each of the identified narration properties while Figure 9 depicts the popularity of the narration control actions.

According to the 4^{th} group answers, 77.5% of the respondents had some sort of experience with haptic exploration of cultural objects, while, as it was expected, they all strongly

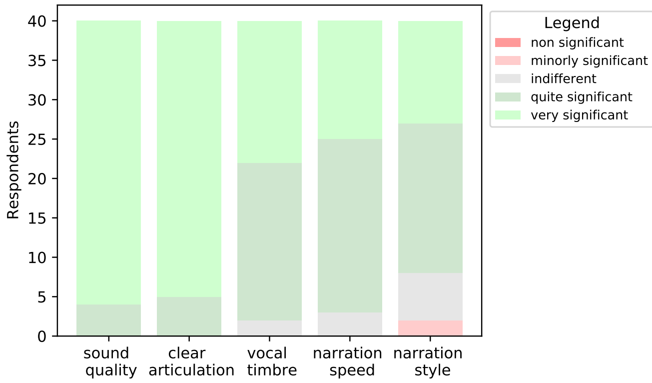


Figure 8: Respondents narration properties preferences. The significance of each of the five primary properties of a narration are illustrated as a stacked chart. Sound quality and clear articulation are found to be the most favorable properties while for a small amount of the respondents the narration style is non significant.

agreed on the significant benefits of haptic exploration of 3D replicas that allow them to recreate a mental *visualisation* of an exhibit. Through the discussion though, it was understood that their haptic ability varies due to a wide range of factors. Since almost half of them were not born VI, they did not seem to have developed their haptic exploration skills to the same extent as those who were born visually impaired. In addition, the respondents underlined that the haptic exploration specifically of a tactile map of a visiting area would allow them to navigate around with more confidence and even perceive an exhibition as a whole, instead of being presented with individual artefacts.

The aim of the 5^{th} part of the questionnaire was to outline the opinions and knowledge of the respondents regarding the use of digital applications and smart exhibits and replicas in spaces of cultural interest. Only 22.5% of the respondents have used portable accessibility devices in such spaces, even though they use them extensively in their daily lives. However, the respondents found very interesting and useful the concept of an SE with active feedback. Both the availability of explorable replicas (72.5%) for artefacts and their interactive nature (62.5%), with on-demand (integrated trigger buttons) audio content, are deemed as very welcomed and important, to their experience, additions.

Most of them however did point out that a trial period with additional guidance regarding the use of an SE would be necessary in order for them to feel more comfortable with such devices and explore its full potential. All these will operate as a guide not only for the development of the actual systems but also for the training needed for the museum staff and the VI visitors.

4.2. Haptic performance results and analysis

In task one, more than 50% of the VI (VIg) and the non-VI (nVIg) group respondents pointed out that they can discriminate a gap down to $1 - 0.5mm$. This can be considered as a mean reference point for haptic sensitivity for those who have trained their abilities and for those who have not. Most of the respondents replied that a vertical haptic tracing approach helped them

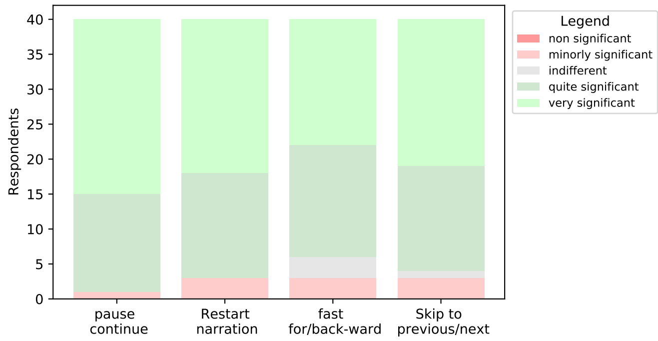


Figure 9: Respondents' preferences in relation to narration control actions. The ability to start and pause a narration at any point is found to be as the most popular feature. Overall, all actions are considered welcomed features.

identify the gaps more efficiently. This approach drove the majority of the VIg to further enrich their exploration with tapping the top and bottom edge of the gap (very similar to how other haptic sensitivity tests function), while also facilitating other parts of their fingers (e.g. nails). The nVIg also acknowledged the efficiency of a vertical approach, but most did not manage to adapt or expand their exploration techniques.

In task two, both groups pointed low-profile button triggers as more preferable. A 56.7% of the VIg choose the first trigger (5.0mm) and a 36.7% of the respondents choose the next one (7mm). Similar results were delivered by the nVIg for the same trigger profiles (48.1%, 50%). A large number of respondents discussed on the wobbling property of high profile triggers as a risk of misinterpreting their function for a miniature control stick. They also pointed out that such triggers would be prone to malfunctions due to forceful use and mishandling. A small number of VIg respondents expressed the preference to place triggers on a designated area and avoid their scattering on an artefact's surface. This would allow them to separately focus on haptic exploration and then on the *smart* functions activation.

Task three was rated as the most difficult route to follow (40% VIg, 50% nVIg), as the complexity and density of meanderings at specific points resulted in numerous haptic retracing attempts. The nVIg found the meanderings even more challenging (15% more than VIg) to trace, acknowledging their inefficiency in filtering out irrelevant haptic information and

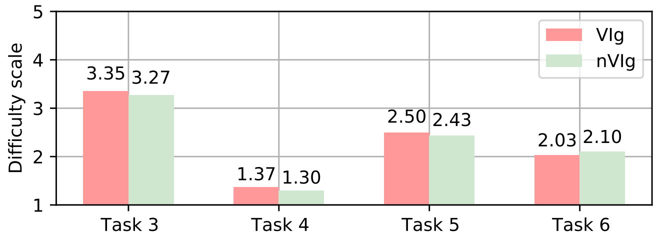


Figure 10: Haptic route tracing tasks performance. Evaluation results are presented for both; VI and nVI groups. A low value indicates a less challenging task. The VIg and nVIg variances per task were: 1.19 & 1.53 — 0.36 & 0.34 — 1.08 & 1.18 — 1.33 & 1.56. indicating that the 4^{th} task was found to be the least challenging by all the respondents.

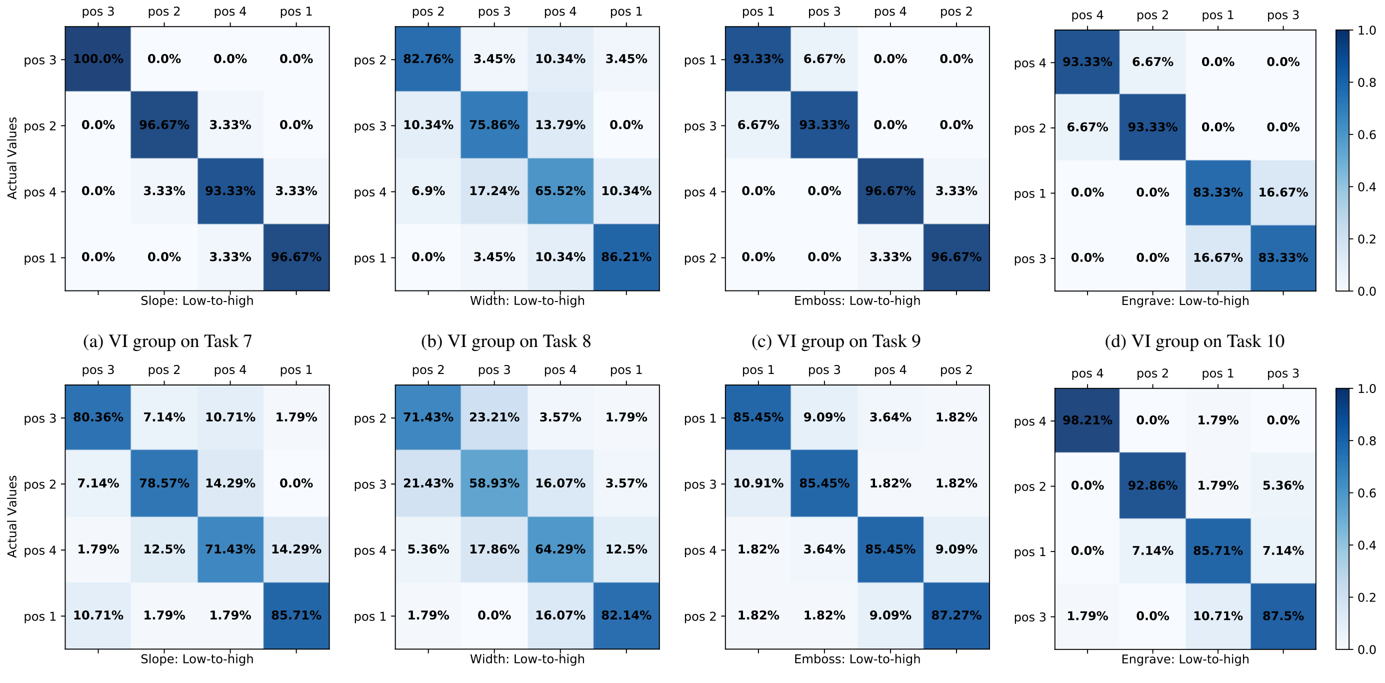
focusing on the primary target (route). Despite the difficulty, an 80% of VIg respondents agreed that meanderings may allow a better route memorisation due to their strict use of vertical and horizontal lines. This reaffirms the importance of orientation and their explicit desire for features that enhance perception of direction. The $2mm$ width and $1mm$ emboss height of the 3D printed route line has been characterised as adequate from the respondents (70% VIg, 54.7% nVIg), but still a considerable number (23.3%VIg, 7.7%nVIg) believes that a more embossed one ($> 1mm$) would benefit haptic tracing. The triangle shape at the end of the route was seamlessly recognised by the majority of the respondents (96.7% VIg, 94.3% nVIg), with only two from the VIg specifically identifying it as a equilateral one.

On the other hand, the route of the fourth task was ranked as the easiest to follow (76.7% VIg, 66% nVIg). All of the respondents have managed to detect the square shape at the end of the route while more than 90% (93.3% VIg, 98.1% nVIg) perceived the brevity and immediacy offered by such routes.

The route of the fifth task was ranked, in terms of tracing difficulty, between the routes of the 3^{rd} and 4^{th} tasks (50% VIg, 40%$nVIg$ rated at $2/5$ while 35% VIg and nVIg rated at $3/5$ where higher values indicate a more challenging task). The pentagon at the end of route was the most challenging shape for both groups to identify (only 30% VIg and 40.4% nVIg were successful). At that scale a pentagon features much smaller sides (than any other shape) and obtuse angles, making them hard to recognise and count (without counting twice). One out of two respondents recommended that a more embossed dash-based route would provide better tactile feedback and thus allow a more confident exploration of complex routes (Dash dimensions as shown in Figure 7: length 2.2mm, emboss height 0.45mm, width 1.4mm).

Dot detection in the route of the sixth task was very welcomed and intuitively completed by, familiar with Braille, VIg respondents. A few exceptions gave a higher difficulty score, addressing the misinterpretation of the tactile information as a Braille sign that had to be read. The route was ranked easy (43.3% Vig and 41.5% nVIg rated at $1/5$) and by 10% more VIg than nVIg respondents stated that dots did not affect their ability to detect the locations where route direction changed. Almost everyone was successful in recognising the circle at the end of the route (only $< 2\%$ of the respondents failed). A higher number of nVIg respondents ($> 15\%$ more than VIg) discussed the need of a higher embossed dot.

Figure 10 illustrates the performance of both groups in every route-tracing task (Tasks $3-6$). Based on the results of these tasks, the presence of dense information in tactile routes escalates the difficulty of palpation and the requirements for haptic filtering. Additionally, horizontal and vertical route orientations are strongly advised when designing embossed routes that translate directions. An embossed triangle as well as a square are easily distinguishable objects and qualify for efficient tactile representations of pointers and annotations. It is worth mentioning that several VIg respondents detected and discussed the embossed cylinder that frames the shape at the end of each route. Some even used the protruded knob at the start of each route (of increasing width) to distinguish and switch between



(e) nVI group on Task 7 (f) nVI group on Task 8 (g) nVI group on Task 9 (h) nVI group on Task 10

Figure 11: Normalised haptic performance of the VI and the nVI groups on identifying the correct (min to max) sequential escalation of the elements' properties presented in tasks 7-10 (slope, width, emboss and engrave respectively). Each matrix is organised according to the correct sequence of the four distinct elements of each task. The diagonal holds the correct answers, while on the remaining cells of each row are the available possible options per ranking position. Hence, the more compact the diagonal is, the more correctly identified is the sequential order of the elements over the respondent population (VI and nVI groups).

them. A VIg respondent mentioned that sharp angles design should be avoided as they may injure the skin of fingers. Furthermore, dashed routes are found to increase haptic stimulus in a favourable manner, and as such their combination with dots (between dashes) may allow for another efficient encoding method. Diversifying the tactile information of each path provided the VIg with stimuli to adapt and enrich their scanning methods, employing more fingers (one hand or two hands) and different search strategies (spirals, zigzags and parallel sweeps) [**?**]. Line and dot scanning are both methods used in similar research to evaluate and score the ability to understand tactile information and follow raised paths without losing contact. Scanning skills are directly linked with the efficiency of exploratory hand movements and their use to capture all the tactile elements before understanding the thematic context. Shape and size interpretation have also been common assessment methods for discrimination skills and for the ability to match and compare items based on tactile properties [**?**].

All the above simply reveal the VIg trained capacity to detect, absorb and capture the maximum amount of available tactile information with the single goal of enriching their perception and providing more context.

Tasks 7 – 10 focus on the evaluation of haptic memory and accuracy. Cross examining four protruded rectangles, the respondents are asked to measure and detect small variances on aspects of geometry that are commonly used to encode tactile information.

The results of the seventh task is a strong indicator that discriminating between different surface slopes is not very challenging. This tasks offers accessible edges and sides that reflect small variances in slope and thus facilitate easy haptic detection. Respondents were successfully triggered to use four finger simultaneously examining slope differentiation. Nonetheless, a small slope difference (20^o - 25^o) in this task proved to be more challenging to detect across all groups. VIg respondents discussed positively the exploitation of slopes as a design practice to indicate a height difference as a ramp.

Task eight was the most challenging in this set. It required enhanced tactile exploration abilities to determine the different width of rectangles of the same height and small in-between gaps ($\sim 2mm$). Comparing the results between the two groups shows a slightly better haptic performance for the VIg. Instead of relying on haptic friction the majority of VIg pressed the sides to increase the stimulus from edge and corners. Two respondents resigned from completing the task while a number of respondents exploited the use of nails to determine the borders and detect the gap for each embossed rectangle.

Oppositely, task nine had the best performance results. The ability of all respondents to detect the different height embossed rectangles was depicted by a 95% success for the VIg and 84% for the nVIg. This is a strong indicator for encoding information using different heights even with multiple and/or of small range variations ($\geq 0.5mm$).

Task ten is the opposite of task nine. Respondents were requested to determine the depth variations between four engraved rectangles. The performance was similar to the previous task with a slightly higher number of erroneous answers for the rectangles (3^{rd} position) with depth > $1mm$ which probably introduces a challenge for the average sized finger tip). Both groups showed similar performance in detecting depth variations, with VIg appearing less erroneous than nVIg. Based on the results, engraving information is also considered a good practice but high depths (> $2mm$) should be avoided for complex and narrow cavities. It is worth noting that VIg respondents were the only ones attempted to determine depth using the little finger.

Figure 11 depicts the normalised haptic performances of the VIg and the nVIg for tasks $7-10$. Studying the confusion matrices, tasks 7 and 9 are found to be the least challenging to complete by both groups. VIg outperforms nVIg in every task; proof of their enhanced haptic ability and extended haptic memory.

In terms of good 3D printing practices, varying sloped and embossed surfaces are found to be fairly easy to compare and distinguishable. This finding complies with the elements used for tactile floor planning in [16]. Using 3D objects and comparing between embossed shapes has been employed in related research and more specifically in haptic battery tests that measure symmetry and evaluate short and long-term memory with familiar/unfamiliar objects. Such parameters are very relevant with the experience of a SE, where 3D printed objects and tactile surfaces aim to deliver previously unknown geometries with common annotation conventions respectively [17]. Further asserting the significance of 3D elements, [18] concludes that combining 3D with flat relief symbols (2D) improves the memorisation of tactile keys, since the 3D attributes can be more effectively distinguished from the 2D features by touch.

On the other hand, measuring and perceiving width and length seems to be a significantly harder task and one that requires acute haptic sensitivity. Encoding of information using varying surface distances (e.g. width, length and height) should be avoided, if not used as an assessment method. Efficient recognition of engraved tactile information is tightly linked to its geometry and the accessibility constraints. Our study indicates that a minimum requirement of $1-1.5mm$, for embossed (height) and engraved (depth) information, will ensure efficient haptic recognition and confident exploration given the used 3D printing settings. Although, taller than the standard Braille dot profile (0.5mm) [19] such a requirement could make the exploration of unknown tactile content more efficient for less skillful users. Such declarative tactile information is also advised for boundaries of any surface representing a thematic subject or element that should be separately explored and understood. This delimiting approach allows for the encoding of information domains that can be easily identified by all fingers using different angles and techniques (e.g. friction,pressure, tapping, pinching).

Evaluating the overall design and build, most respondents described the size of the 3D printed object ($18cm$ x $10cm$) as suitable for tactile exploration (76.7% VIg, 59.6% nVIg), while a total of 25% expressed the opinion that it should be larger in order to support a wider task spreading. The triangle shaped task indicators were well accepted by the majority of the respondents (75%), while a 10% mentioned that the object orientation indicator should be larger. Row-based triangle topology found to be more tactile friendly than column-based. The texture of the 3D printed object felt well-balanced between smooth and rough (93.3% VIg, 66% nVIg). This verifies Wilson et al. [20] extensive research on 3D printed replicas physical properties; that having good quality prints is not necessarily important, provided that it is at least of sufficient quality. Hence, the printing properties of the assessment object are found to be suitable.

Moreover, the completion times of the haptic assessment span between $11-28$ minutes for the VIg and $12-28$ for the nVIg. The average times for completing the assessment were 20 and 18.5 minutes respectively. Again, although the completion times of the nVIg respondents are smaller this does not indicate a higher performance. Comparing tactile information can easily lead to misconceptions when untrained senses drive rough assessments. The nVIg presented limited knowledge of how certain haptic techniques couple with specific tasks and how time should be invested. The VIg proved that thoroughness and versatility can help develop the type of memory that effectively accumulates useful tactile information and successfully compares haptic feedback.

4.3. Smart exhibit properties analysis

According to our results analysis and within the APTOS framework, a SE is defined as a smart device adapted to exist within the operational framework of a museum and aimed towards coupling tactile interaction with haptic exploration and on-demand narration. In this scope and towards delivering the three targeted SE prototypes, the following properties have been selected to profile their functional, non-functional and contextual/experiential aspects:

1. Functional:
    - It will offer simple mechanisms for user-exhibit binding procedures such as close approximation between the exhibit and a smart/wearable device.
    - It will offer distinct event triggers located in positions that reflect the availability of additional relative information in the form of narrative content. Trigger topology may not be always congruent with narrative content in order to serve specific cases of artefacts' morphological features.
    - Its hardware components will allow Internet access and/or inter-networking with other smart devices and/or a central control point.
    - It will have the ability to monitor and detect events or even to record parameters or commands provided by its environment or its user.
    - It will have the ability to locally process and analyse events and/or parameters being recorded and/or to transfer them to other devices.
2. Non-functional:
    - It is tangible and has been created by technologies such as 3D digitisation and 3D printing and will faithfully

replicate, up to a given and desired extent and scale the morphological features of an actual artefact.

- Its morphological features may have been processed in a way that enable an enhanced interaction and a better understanding through tactile exploration, overcoming limitations related to the lack of authenticity.
- It may be adapted to be experienced in non-designated areas to overcome VI access challenges and/or it can be a part of a pre-, during and post- museum visit experience.

3. Contextual/experiential:

- It may act as an alternative energiser of visitor attention, balancing both physical and mental contact with museum content, through adaptable hands-on activities and narration.
- It may add value to the whole museum experience (to selected artefacts, themes, interpretations, stories etc.), serving as a communication mediator to both visitors and museum professionals.

The above properties derive from the APTOS project's targeted outcomes and application domain. Although they do not aim to define a SE's complete profile, they contribute in clarifying a context for enhancing the VI-cultural heritage interaction. An interaction that will be experimentally tested and evaluated within the project's framework.

5. Conclusions

The accessibility of museum collections by the visually impaired is a multidisciplinary research domain. ICT may play a significant role in providing assistive methods that enable individuals to access museums' reserve through multimodal approaches that are not limited to the actual premises of a museum. The elimination of the ”Do not touch” ban in conjunction with on-demand narrative enrichment triggers the general interest and initiates a further involvement in comprehending the cultural and historical background encapsulated by exhibits.

We presented a smart exhibit through a high level description of functionalities that are required to enable the delivery of practicable and of low-cost interactive systems that are focused on allowing the visually impaired to experience museums' reserve. We followed a user-centered approach to efficiently collect and thoroughly interpret requirements and opinions before we initiate the prototype systems development. A specifications questionnaire along with a custom-built haptic performance assessment were used. The first allowed the examination of the visually impaired requirements, preferences and attitudes when it comes to museum visits along with their technological tools familiarity that enhances accessibility and their opinion on the primary aspects of the proposed smart exhibit functionality. The second allowed to determine properties of the human haptic performance in relation to several 3D printing settings, morphological, topological and dimensional feature preferences and design elements.

Currently, we are working on the implementation of the experimental systems that are based on the proposed smart exhibit framework and the requirements specifications and user preferences presented in this work. A total of three systems are currently being developed. These are *aptos.Exhibit*, a multi-user smart exhibit based museum exhibition, *aptos.Map*, a standalone interactive tactile museum premises map tool and *aptos.myExhibit* which is a museum-kit that enables museum reserve exploration after the completion of an actual museum visit through miniature 3D prints. All systems will support on-demand narration and will be installed in the Epigraphic Museum (Athens, Greece) for further evaluation and optimisation.

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Appendix A

Table A1: Haptic performance assessment object analysis.