Evaluation of the Pure-Form Haptic Displays Used for Exploration of Works of Art at Museums

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Abstract

The Museum of Pure Form is a virtual reality system where visitors can interact with digital models of sculptures through the sense of touch.

The paper presents the results from the evaluations of the Pure Form system conducted during 2003 and 2004 at several exhibitions held in European museums.

1. Introduction

Haptic perception represents the most immediate and intimate way of interacting with sculptures and other art objects, allowing the observer to perceive the concept of space the artist has impressed on the art forms during their formation. For reasons of security and preservation, visitors to traditional museums are allowed only to see the objects, and, since touching them is not permitted, this experience falls short of a full appreciation of the artistic value and intrinsic beauty of the collections. Moreover, the appreciation of visual art is often denied entirely to blind and visually impaired visitors. Through the conjunction of virtual reality (VR) and haptic technologies, the Museum of Pure Form aims at offering an alternative by giving the haptic perception of artistic forms an approximation of the same essential role it had for the artists during their creation.

Various examples exist of systems where haptic interfaces are used to interact with art forms. Most of such examples are based on using haptic devices as synthesis tools (see for instance [17][18]). Less often haptic devices have been used as tools for better analyzing art pieces. The only existing example of this, to the authors’ knowledge, is the work of McLaughlin and her group at USC [15].

Funded by the European Commission under the 5th Framework Programme’s ‘Digital Heritage and Cultural Content’ key action area (IST 2000-29580), the Museum of Pure Form [1][16] aims to explore new paradigms of interaction with sculptural pieces of art, and to create a virtual gallery featuring three-dimensional digitised sculptures from European and worldwide museums with which visitors can interact using their senses of touch and sight.

Figure 1. The museum installation at CGAC site.

Project development was carried out by a consortium of partners coordinated by PERCRO. Several museums were involved in the project. The Galician Centre for Contemporary Arts (CGAC), Santiago de Compostela (Spain), the Museo dell’Opera del Duomo (OPAE), Pisa (Italy), and the Nationalmuseum (NM) of Fine Arts, Stockholm (Sweden) actively participated in the project by hosting and organizing public temporary exhibitions. Other associate museums that have contributed to enrich the digital collection of works of arts were the Conservation Centre at National Museums Liverpool (UK) and the Petrie Museum of Egyptian Archaeology, London (UK).

The Museum of Pure Form has had a number of deployments in cultural heritage institutions across Europe. In September 2003 a new multimedia room was opened at OPAE, while formal evaluation of the project in a CAVE-like environment [10] took place at University College London in November 2003. This has continued at CGAC and at the NM during the first three months of 2004.

At CGAC the Pure Form systems were exhibited throughout the month of February. More than 400 users explored the potential of haptic interfaces for engagement with artworks. In Figure 1 it is shown the complete set-up
of the Pure Form system, as it was installed in CGAC during the exhibition held in the museum. The exhibition at NM was arranged in cooperation with the museum staff (especially Hans Öjmyr) and the staff of the Interactive Institute, Stockholm (especially Halina Gottlieb), in March and April 2004 in connection with a larger exhibition “False and Genuine” featuring genuine works of art and different kinds of copies, authorized as well as forged. The virtual works of art to be explored haptically were here considered as a special kind of copy.

This paper presents the results of the evaluations that were conducted at the different exhibition sites during 2003-2004.

2. Overview

The complete Museum of Pure Form system is composed of the following components:
1. the haptic interface system
2. the database of the 3D models of sculptures
3. the stereoscopic visualization system
4. the software API (Application Program Interface) libraries for the haptic and graphics rendering.

The overall system architecture is schematized in Figure 2. The simulation and control of the Haptic Interface system are deployed over 2 computing nodes, which have been implemented on a low-cost platform composed of two PCs.

2.1. General description of the system

The need of a more realistic haptic interaction in VE has encouraged the development of devices that make use of multiple points of contact [12], when the interaction is not tool-based. In the Pure Form system two haptic devices have been specifically devised in order to provide the user forces on two contact points on the hand. They are an exoskeleton device and a desktop device.

The anthropomorphic exoskeleton device can be worn on the operator arm, as shown in Figure 3, and can globally exert forces of arbitrary direction and amplitude on the index and thumb fingertips, along all over the whole workspace covered by the arm.

The Pure Form desktop device is composed of two distinct robotic arms departing from two support columns placed in front of the visualization screen (Figure 4). They reach the fingertips of the operator’s hand with thimbles that can be worn on two fingers either of the same hand or of two different hands.

In the museum exhibitions the simulation of the virtual environment was displayed through a stereoscopic visualization screen with back projection and passive polarization. The dimensions of the screen were 2m width by 1.5m height. The projection screen was fixed through a frame and the haptic interface was placed in front of the screen.

Seventeen sculptures belonging to different historical periods were digitized through laser scanning and post-processed to produce accurate polygonal meshes. The count of polygons of meshes was then reduced in order to reduce the complexity of the models and improve the performance of both haptic and graphic rendering algorithms (Figure 5).

The characteristics of digital models generated by a 3D laser scanning process, constituted as they are by a large number of polygons and moreover very densely distributed over the surface, make these models very hard to be haptically rendered in real time with conventional algorithms. The generation of the force information was realized through a constraint-based algorithm, based on
the god-object concept introduce by Zilles and Salisbury [13]. A detailed real-time haptic rendering of surface of the model was achieved by running the force generation module on a local model of the contact area, while the collision detection was conducted in a separate thread on the whole model.

3. Problem

The aim was to evaluate the PURE-FORM haptic displays used by museum visitors manually exploring virtual copies of statues and at the same time obtaining a stereo visual copy. The results from evaluations at three museums, OPAE, CGAC and NM and from experiment conducted at the ReaCTor facility of UCL are reported.

4. General method

The PURE-FORM desktop device was used at OPAE museum, while the PURE-FORM exoskeleton haptic display was used at all remaining locations.

Questionnaires were used at all museums. The questions were partly common in the different contexts, but they were also partly different depending on local conditions. The general content of the questionnaires was a result of cooperation between representatives for the partners of PURE-FORM and the museums involved in the evaluation. It consisted of questions about the experience of specific parts of the statues, ratings of general aspects of the usability of the device and the personal background of the participants. In the present report a summary of the evaluations is given with references to original preliminary texts.

5. Evaluation within a multimedia exhibition at OPAE

The PURE-FORM display at OPAE was part of a larger multimedia exhibition providing a virtual visit to the area, the Miracle Square, including as well the Dome and the Leaning Tower. The evaluation was performed in cooperation with the staff of OPAE. Details of the questionnaire, as well as the results are given in [2].

The available virtual statues were five sculptures of the Italian gothic period by Giovanni and Andrea Pisano. The questionnaire, available in Italian and English and given to about 150 museum visitors, consisted of 20 questions, most of them with answers in multiple choice form.

5.1. Results

The time spent with the PURE-FORM desktop haptic display was estimated to be more than five minutes by about half of the number of visitors and a majority (93 %) touched the virtual statues. Most of them found the experience amusing (73 %) and/or instructive (61 %).

6. Evaluation within a CAVE-like environment

A CAVE-like room (CAVE Automatic Virtual Environment [10]), i.e. a room with floor and 3-4 walls back-projected with a stereoscopic visualization of a virtual computer-generated scenario, was used for the experiments. The tests were conducted within the
ReaCToR at the Department of Computer Science, University College London. The PURE-FORM exoskeleton haptic display was installed. Visitors could navigate through a virtual museum, select a virtual work of art from the Petrie Museum or OPAE and interact with it (Figure 6). In total 2 statues were chosen to be made available during the tests.

Figure 6. The interaction with statues during the simulation in the CAVE-like environment.

6.1. Methods

A main part of the evaluation concerned co-location of stereo graphics and haptic display information. A group of 6 computer-literate adults (50% male, 50% female) were invited to take part to the experiment. A simple task was set, the users being asked to explore the shape of two statues wearing the exoskeleton haptic device respectively with force feedback enabled and disabled. Each task took lasted five minutes and statues were presented in different orders. After the completion of the exploration, the users were asked to complete a questionnaire with 30 questions, of which 7 dealt with the sense of touch and 9 with the sense of presence. Two other additional questions dealt with the user’s observation of the environment.

The answers were given on the basis of a 1 to 7 Likert scale.

6.2. Results and discussion

The analysis of results, even if based on a limited sample, evidenced a significant difference between the means of answers related to the sense of touch for the condition with and without haptic feedback (Mann-Whitney U test, p<0.001).

All the scores in the touch-related set of questions were above the midpoint of the scale for the haptics on condition. For instance Question 8 (“Did you feel you were touching the statue”) scored a mean of 4.4 with SD = 1.12 vs. 1 with SD = 0, while Question 11 (“To what extent could you feel the different curves and shapes of the facial features?”) reaches a mean of 5 with SD = 1.1 vs. 1 with SD = 0, respectively for the two conditions of haptics on and haptics off.

No significant differences were observed in the set of questions related either to the observation of the environment and to overall sense of presence, even if higher scores where obtained in questions related to presence and a higher number of errors were committed in the description of the environment in the condition with haptics on.

Informal observations [2] indicated that co-location was very important to enhance the experience, but it was also found that some participants had problems to visualize a 3D stereo object and focused on the front wall instead of the 3D position of the stereo model. This led to a discrepancy between visual and haptic information and loss of the stereo effect. A planned solution was to place the haptic interaction as close as possible to the projection wall.

7. Evaluations at CGAC and at NM

The PURE-FORM exhibitions in Santiago de Compostela and Stockholm had much in common both in the general arrangements and in the questionnaires presented. However, there were also differences and the evaluations are partly presented separately. A more detailed report of both evaluations was given in [2].

7.1. The exhibition at CGAC

7.1.1. Methods.

The participants had to choose two statues for exploration among seven available ones.

The questionnaire was presented, in Spanish, Galician and English versions, and collected from 127 visitors, 69 women and 58 men with a mean age of 28 and 31 years, respectively, in both cases SD = 9 years. A majority (56 %) reported to be frequent visitors to the museum (at least at a monthly basis). About one third had heard about the exhibition by word of mouth, another third from personnel at the ticket office.

All statistical evaluation was carried out using non-parametric tests. Correlation factors were computed using the Spearman rank test, while comparison of means was made through Mann-Whitney U statistics.

7.2. The exhibition at NM

7.2.1. Methods. Two statues were used in the evaluation, Saint John by Andrea Pisano. and the “The thorn extractor” by an unknown artist (marble copy of a Roman bronze sculpture), and all visitors explored both, with the order of presentation varied between them. The exploration time was between 3 and 28 min (M = 8 min, SD = 3 min). The questionnaires (presented in Swedish and English versions) were given after the exploration
and filled in individually by the visitors in their own pace outside the exhibition area.

Usable questionnaires were obtained from 115 sighted visitors (Mean age = 33 years, Range = 13 – 71, SD = 14 years). About two thirds were men, and nearly the same proportion had a university degree. Only a minority (13%) had earlier experience of virtual reality or similar installations.

Two-thirds reported never or rarely playing computer games, while the self-reported experience of computers had a mean of 5.5 on a 7-degree scale.

The questionnaires from six blind visitors will be analyzed, as well as those from 13 visitors who took part when only one of the two fingers of the display was functioning.

7.3. Results

7.3.1.  Haptic experience of specific parts of the statues. The questions on this subject were typically of the following form: “To what extent could you feel the shape of X” with the answer given on a 7-point scale. The specific parts concerned at NM hair, beard, face, breast, back and clothes and the means varied between 3.8 and 5.3 with SDs between 1.5 and 2.0. At CGAC the features were pressure and volume, curves and shapes of the facial features, and the shape of the dress and body features with means between 4.1 and 5.1 and SDs between 1.6 and 1.8.

In sum, all the means except one were above the middle point (4) of the scale. The exception was the back of a sculpture that apparently was more difficult than the other features; the visitor had to explore from behind.

7.3.2.  The feeling of touching a statue.

A general question at both museums about the exploration with the haptic display was “Did you feel that you were touching the statue?” with an answer on a 7-point scale. The means of the answers for the four statues at the two museums varied between 4.2 and 5.0 and the SDs between 1.7 and 1.9, thus again over the middle point of the scale.

7.3.3.  Factor analysis of questionnaire answers at CGAC. A factor analysis of a selection of answers at CGAC was undertaken in order to identify some main factors underlying the visitor experience and determining the final judgment of the overall exhibition (Table 1, Table 2; for details, see [2]).

The questions can be grouped in several sets and reduced in number according to the results from the factor analysis that was conducted through a Principal Component Analysis (Varimax with Kaiser Normalization).

This division in sets led to the identification of six factors that were able to account for the 75% of the variability observed among subjects’ answers. The expression of the 6 factors is reported in the tables below, together with the relationship of each factor with the items that compose it.

Table 1. List of the principal components identified from the factor analysis

<table>
<thead>
<tr>
<th>Factor</th>
<th>Questions</th>
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<tbody>
<tr>
<td>F1: Haptic experience</td>
<td>Q5</td>
</tr>
<tr>
<td></td>
<td>Q6</td>
</tr>
<tr>
<td></td>
<td>Q10</td>
</tr>
<tr>
<td></td>
<td>Q11</td>
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</table>

Table 2. Composition of principal components as derived from factor analysis

<table>
<thead>
<tr>
<th>Principal components from factor analysis</th>
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</thead>
<tbody>
<tr>
<td>Q5</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>.808</td>
</tr>
<tr>
<td>.858</td>
</tr>
<tr>
<td>Q10 (1)</td>
</tr>
<tr>
<td>Q11 (1)</td>
</tr>
<tr>
<td>Q13</td>
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<tr>
<td>Q14</td>
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<tr>
<td>Q15</td>
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<td>Q8</td>
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<tr>
<td>Q16</td>
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<tr>
<td>Q18</td>
</tr>
<tr>
<td>Q21</td>
</tr>
<tr>
<td>AGE</td>
</tr>
<tr>
<td>Q19</td>
</tr>
<tr>
<td>Q4</td>
</tr>
<tr>
<td>Q20</td>
</tr>
</tbody>
</table>
The above 6 factors allows to carry out the analysis of results on a reduced set of variables and to better highlight the relationships among them.

The most important factors found were related to Haptic experience (F1), Device usability (F2) and Added value of haptic experience (F3) as detailed in Table 1. Factor F1 mainly refers to the ability of persons in getting a realistic feeling of touch in the VE, while F2 represents the usability and satisfaction of usage of the device, and F3 the added value that visitors perceived from the experience in the VR. Factors F4, F5 and F6 are instead related to the visitors profile.

**Table 3. Correlation between principal factors, age and Q22 (Spearman rank test)**

<table>
<thead>
<tr>
<th>Age</th>
<th>Q22</th>
<th>R</th>
<th>p</th>
<th>N</th>
<th>R</th>
<th>p</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.76</td>
<td>.003</td>
<td>113</td>
<td>.939</td>
<td>70</td>
<td>-0.09</td>
<td>71</td>
<td>.191</td>
</tr>
<tr>
<td>0.142</td>
<td>2.142</td>
<td>70</td>
<td>.600</td>
<td>71</td>
<td>0.06</td>
<td>71</td>
<td>.133</td>
</tr>
<tr>
<td>-0.133</td>
<td>.268</td>
<td>71</td>
<td>0.06</td>
<td>71</td>
<td>0.334</td>
<td>71</td>
<td>.264</td>
</tr>
<tr>
<td>-0.758</td>
<td>.000</td>
<td>71</td>
<td>0.276</td>
<td>71</td>
<td>0.027</td>
<td>71</td>
<td>0.306</td>
</tr>
</tbody>
</table>

**7.3.4. General judgment.** Visitors were asked to rate their general opinion on the system (Q22: “Write your general opinion about the Museum of Pure Form”). In CGAC answers, the general opinion Q22 that persons have expressed was positively correlated with F1 and F3, but with F2, and negatively correlated with age (Table 3). The evaluation results provided a strong indication that the final judgment of the system was expressed on the basis of the quality and added value of the haptic experience; moreover younger people expressed in general more positive comments. Questions related to the experience in VR with respect to a traditional one. A significant correlation was found with answers to Q5, Q6, Q8, Q10 and Q11 that are all related to the haptic experience (F1). This indicates that the haptic experience by itself was considered as an added value.

**7.3.6. The usability of the haptic display.** Three questions at both museums concerned general aspects on the usefulness of the display:

(1) It was easy to learn to use the device (Q13).
(2) I felt comfortable using the device (Q14).
(3) Overall, I am satisfied with the device (Q15).

The answers were given on a 7-point scale from “strongly disagree” (1) to “strongly agree” (7). The result is given in Table 4.

**Table 4. Results of usability questions at the two museums**

<table>
<thead>
<tr>
<th></th>
<th>CGAC</th>
<th>NM</th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to learn</td>
<td>126</td>
<td>114</td>
<td>3.2</td>
<td>5.1</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Comfortable</td>
<td>124</td>
<td>115</td>
<td>3.4</td>
<td>5.1</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Satisfied</td>
<td>126</td>
<td>114</td>
<td>3.4</td>
<td>5.1</td>
<td>1.9</td>
<td>1.6</td>
</tr>
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<td></td>
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</table>

From the analysis of answers of CGAC test, it is found that the answer to Q15 was significantly correlated with those to questions Q5 (R=-0.294, p=0.001), Q6, (R=-0.256, p<0.004 (1), R=-0.230, p<0.02 (2)) and with Q13 and Q14, too. This means that in general the user’s satisfaction was strictly dependent on their haptic experience.

The wish of finding similar installation (Q17: “Would you like to find similar installations?”) was found to be strongly dependent on the overall satisfaction with the system (Q15, R=-0.259, p=0.004) and the overall learning from the experience (Q16, R=0.199, p=0.027).

**7.3.7. Amusement/instructiveness of the experience.** At CGAC 70 % of the visitors answered that they found the experience amusing and 39 % that they found it instructive. At NM the answer was given on a 7-point scale with 1 as low judgment and 7 as high judgment. The experience was evaluated on average as amusing (mean score 6.2 with SD 1.0) and instructive (mean score 5.6 with SD 1.2).

**7.3.8. Suggestion and wishes from visitors**

At CGAC 96 % of the visitors reported that they wanted similar devices at other museum. At NM the answers were given on a 7-point scale as in the earlier questions. On average visitors expressed their willingness of suggesting the visit to friends (mean score 5.7 with SD 1.5) and wanting similar devices (mean score 5.7 with SD 1.6).

**7.3.9. Effect of age.** Age influenced the general opinion expressed on the system, as it was found to
negatively correlated with general judgment (Q22) in answers at CGAC.

Moreover the visitor profile (factors F4, F5 and F6) was dependent on age, as it is shown from the correlation factors in Table 2.

The habit of playing video-games was negatively correlated to the age, and this determined also the level of amusement that was derived from the experience (Q18). A positive correlation was observed between the habit of playing videogames Q21 (that was measured on a 7 points scale) and Q8 (R=0.202 N=125 p<0.025), meaning that people acquainted with interactive pc games better appreciated the usefulness of the haptic experience.

Familiarity with VR systems and with PCs was instead positively correlated with age. People that were more familiar with PCs needed also to ask additional information on the system.

However there was no significant relationship between the level of familiarity with computers and virtual reality, and the scores reported in the other evaluation categories.

7.3.10. **Effect of training.** In the CGAC exhibit two sculptures were randomly presented to the visitors according to the preferences that they expressed. This allowed us to compare the answers related to the haptic experience of the first and second sculpture, and to estimate the effect of training in the interaction with haptic device.

It is evident the effect of training for getting acquainted with the application: if we compare the values of Q6 (1 and 2) and Q11 (1 and 2): there is a significant difference (Mann-Withney test) of the means of Q6 (p<0.0001) and Q11 (p<0.005) for the first and the second sculpture, but the difference is not significant for Q10. Greater scores were achieved during the exploration of second sculpture, thus indicating an improvement in performing with the device (see Figure 7).

7.3.11. **One finger or two fingers used.** In real life more than one finger is used at the same time in most tasks. That number of exploring fingers is important has been shown experimentally concerning identification of objects [3].

The results were much improved already when the number was increased to two. However, the size of the contact area is also important [4][5]. Only increasing the number of contact areas has been demonstrated to be insufficient [6]. This was also shown in a study of the performance of 13 visitors at the exhibition at NM that had information from only one finger available (because of temporary failure of the second finger of the device). There answers were not significantly different from the answers of the visitors with information from two fingers.

![Figure 7. Effect of training during the interaction with two subsequent sculptures.](image)

7.3.12. **Visually impaired visitors.** Visually impaired people, especially those with total loss of vision, have severe problems of accessing information from 2D pictures, even if much effort has been devoted to get them well functioning [7]. One of the main obstacles is the difficulty of haptically getting 3D information from such pictures, and it has been suggested that haptic display may be a partial solution [8][9]. It was planned to include visually impaired visitors in the evaluation at NM, but, unfortunately, it was possible to get only six participants. They are also older than the sighted visitors (M = 47, Range = 29-59). The answers from such a small group may, however, provide indications of a result.

For most of the questions the answers for the visually impaired are roughly the same as those for the sighted, but there are tendencies for lower reported experience of having felt the statues and satisfaction with the display.

The importance for the experience of the statue was judged at Nationalmuseum to be somewhat lower for the visually impaired (M = 4.0) than the added value for the sighted (M = 4.9), which is against the expectations of a higher value for the visually impaired.

The suggestions for improvements are about the same as those given by the sighted. However, one additional suggestion was given by the blind: completion with a verbal description.

The last suggestion is probably a most important one for making the haptic display useful for the visually impaired. The display provides a direct access to 3D aspects of the work of art and is thereby an important improvement in comparison with 2D pictures. However, a major problem remains: to get a rapid overview. Verbal information may contribute to a solution of this problem. This information may be given in an introduction including, among other things, suggestions about suitable exploratory procedures. Verbal information may also be given when specific parts of work of art is touched,
similar to the information provided at tactile maps on a touch tablet [14].

7.3.13. The importance of training It was shown above (section 7.3.10) that already the experience of one statue provided greater values for the next one. More experience can be expected to provide still greater values, as it has been demonstrated experimentally [11] that a considerable improvement can be expected after a few hours of training to use the device. It was not suitable in the present context to arrange with long training sessions and long exploration times with the display, but such arrangements would probably have improved both self-rated and measured performance.

8. Main conclusions

There was a large spread in the judgments; for many questions the whole 7-point scale was utilized. Thus there were visitors who “not at all agreed” or “strongly disagreed” with the positive statements, as well as visitors who “agreed very much” or “Strongly agreed”. It should be noted that the present study was based on self-ratings of performance. Their relations to performance measured with objective methods are uncertain. Such measurements can provide both better and worse results.

However, it is quite evident that the visitors in general found the experience of the haptic display amusing. High mean judgments were also obtained for questions about the instructiveness of the experience, and the positive judgments are in majority concerning the questions about “suggesting friends to visit” and “wanting similar devices in other museums”.

On the other side, the improvements suggested indicate that many visitors wanted to be able to more fully utilize the capacities of the haptic sense, especially to use larger parts of the hands. A haptic display with suitable such possibilities can be expected to be more satisfactory. This conclusion is strengthened by our own and others’ research mentioned above indicating the effects of constraints of the information in all present-day haptic research mentioned above.

Concerning the use of the haptic display for aesthetic experience of objects of art it must be noted that aesthetic aspects have not been covered in this study. The participants’ tasks were to judge the experience of physical properties of the objects of art. A study of aesthetic aspects remains to be done.

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