

## Observed methods of cuneiform tablet reconstruction in virtual and real world environments

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# Accepted Manuscript

Observed Methods of Cuneiform Tablet Reconstruction in Virtual and Real World Environments

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# 1 **Observed Methods of Cuneiform Tablet Reconstruction in Virtual and Real World** 2 **Environments.**

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## 11 *Abstract*

12 The reconstruction of fragmented artefacts is a tedious process that consumes many valuable  
13 work hours of scholars' time. We believe that such work can be made more efficient via new  
14 techniques in interactive virtual environments. The purpose of this research is to explore  
15 approaches to the reconstruction of cuneiform tablets in the real and virtual environment, and  
16 to address the potential barriers to virtual reconstruction of fragments. In this paper we  
17 present the results of an experiment exploring the reconstruction strategies employed by  
18 individual users working with tablet fragments in real and virtual environments. Our findings  
19 have identified physical factors that users find important to the reconstruction process and  
20 further explored the subjective usefulness of stereoscopic 3D in the reconstruction process.  
21 Our results, presented as dynamic graphs of interaction, compare the precise order of  
22 movement and rotation interactions, and the frequency of interaction achieved by successful  
23 and unsuccessful participants with some surprising insights. We present evidence that certain  
24 interaction styles and behaviours characterise success in the reconstruction process.

## 25 *Keywords*

26 Collaboration, 3D Visualization, Virtual Environments, Fragment Reassembly, Artefact  
27 Reconstruction, Cuneiform.

## 28 *1. Introduction*

29 There are a considerable number of cuneiform tablets and fragments in the collections of the  
30 world's museums. Most of the tablets originate from Mesopotamia, the land between the  
31 rivers Tigris and Euphrates which cover modern day Iraq, parts of Syria and Turkey. The  
32 cuneiform tablets were formed of clay taken from the river banks. The cuneiform script is  
33 characterized by wedge shaped impressions on the surface of the clay tablets due to the form  
34 of the reed stylus which was used to write the texts. Cuneiform tablets vary in both width and  
35 length. A survey of tablets (Lewis & Ch'ng 2012) in the Cuneiform Digital Library Initiative

36 database (CDLI) showed that most tablets ranged from 20 to 60mm in size, although some  
37 tablets are larger.

38 As would be expected from cultures at the height of their development, the cuneiform texts  
39 convey a wide range of information, including religious texts, literature, mathematics,  
40 astronomy, medicine, law, letters, royal decrees, contemporary events, educational matters,  
41 and administrative documents like inventories and orders, bills, contracts as well as  
42 certificates of authenticity from traders. The intellectual diversity of the tablet contents is  
43 matched by the variation of the tablet size and condition. This paper explores issues specific  
44 to the field of physical and virtual cuneiform reconstruction, and suggests a system capable of  
45 assisting with the reconstruction of cuneiform tablets using virtual representations of  
46 cuneiform fragments.

47 Projects like the Cuneiform Digital Library Initiative (<http://cdli.ucla.edu>), the Cuneiform  
48 Digital Forensic Project (CDFP) (Woolley *et al.* 2002), and the BDTNS (Database of Neo-  
49 Sumerian Texts - <http://bdts.filol.csic.es/>) have advanced the process of cataloguing  
50 cuneiform collections in the digital realm, and brought collected resources of museums and  
51 universities onto the desktop computer. This has resulted in a reduction in the time required  
52 to search cuneiform archives for text. A networked computer can search through thousands of  
53 text fragments in a fraction of a second, and draw results from multiple resources regardless  
54 of geographical location.

55 Unfortunately, the process of cuneiform tablet reconstruction has not been affected so  
56 positively by the advancement of technology, and the processes employed to rebuild broken  
57 cuneiform tablets still rely on glue and putty. Manual joining of fragments from catalogue  
58 descriptions and pieces in individual collections are still the prevalent methods of  
59 reconstruction. This is partly because existing digital databases pay particular attention to the  
60 textual content of a fragment rather than its exact physical dimensions, which can make  
61 reuniting broken fragments very difficult for individuals without specific training or access to  
62 the original fragments. More importantly, there are limited tools available that allow for the  
63 digital capture and intuitive manipulation of scanned 3D fragments in a virtual environment.

64 The virtual reconstruction of cuneiform fragments presents a two-fold problem. Firstly, the  
65 fragments presented on screen must be sufficiently well defined for a user to examine in  
66 detail and make decisions about placement. The shape of the individual fragments must be  
67 easy to identify when viewed on screen in proximity to other similar fragments, and the  
68 surface of the fragments should be of a sufficient resolution to allow close examination from  
69 multiple viewpoints. Secondly, the nature of the reconstruction task requires fine  
70 manipulation of fragments, and a suitable interface for this task must be considered. As  
71 Poupyrev *et al.* (1997) explain, the manipulation of objects in virtual environments can be  
72 awkward and inconvenient because of the lack of tactile feedback and other interface  
73 considerations.

74 With respect to the problems of representation and reproduction, scholars working with  
75 cuneiform texts have relied until now on manual observation and interpretation of the

76 physical evidence at hand. Whilst these scholars have been diligent in their task, there has  
77 always existed the possibility for error and misinterpretation.

78 In the case of purely lithographic representations of cuneiform tablets, the chances of  
79 transcription and substitution errors have existed throughout the publishing pipeline, as was  
80 noted by the past Keeper of Egyptian and Assyrian Antiquities in the British Museum, E. A.  
81 Wallis Budge (1925). Even photographic representations cannot guarantee a robust  
82 representation of fragments, because the camera orientation, position, and lighting can all  
83 affect the clarity and apparent geometry of the object (Hameeuw and Willems 2011). The  
84 advent of high-resolution flatbed scanners and digital photography has led to the digitization  
85 of cuneiform fragments and the foundation of international online databases like the CDLI  
86 and the Database of Neo-Sumerian Texts BDTNS. Unfortunately, the principal issue of  
87 legibility when representing a 3D shape in a 2D medium remains unsolved. The problem of  
88 accurate representation has been discussed for well over 100 years, and one article in *The*  
89 *Journal of the Photographic Society of London* in 1866 gave specific reference to the  
90 difficulties of representing cuneiform text (Diamond 1864).

91 Research has demonstrated the potential of the technology for 3D cuneiform representation  
92 (Woolley *et al.* 2001), and Anderson and Levoy (2002) suggested the use of 3D visualization  
93 and scanning techniques in the analysis of complete cuneiform tablets. Anderson and Levoy  
94 also provide useful technical information about minimum resolution requirements for the  
95 accurate reproduction of cuneiform tablets with legible text, and although the paper deals  
96 primarily with tablets that have already been reconstructed, the arguments in favour of 3D  
97 representation are still valid for cuneiform fragments. Cohen *et al.* (2004) and Hahn *et al.*  
98 (2007) made use of 3D scanning and visualization technology in the digital Hammurabi  
99 project, which produced high resolution textured scans of tablets, while Levoy's advocacy of  
100 3D scanning and visualization techniques continued in the 2006 paper "Fragments of the  
101 City: Stanford's Digital Forma Urbis Romae Project". In this paper, Levoy explains how  
102 fragments of the Forma Urbis Romae (an 18 meter long map of Rome produced circa 206  
103 CE) were laser scanned and reconstructed using inscribed surface topology and fragment  
104 edges. Their paper also discusses the value of manual tagging of topographic features as a  
105 key for future reconstructions.

106 There is evidence that 3D scanning can provide appropriate virtual representations and open  
107 the field of virtual reconstruction to the automated techniques of computer assisted  
108 reconstruction seen with skull fragments in the fields of bioarcheology, palaeoanthropology,  
109 and skeletal biology (Gunz *et al.* 2009; Kuzminsky & Gardiner 2012), and also with pot and  
110 plasterwork in the fields of pot and fresco reconstruction (Brown *et al.* 2010; Karasik *et al.*  
111 2008; Papaioannou *et al.* 2002). The wider academic community provides many examples  
112 where an increased understanding of a subject has resulted from the analysis of 3D data. The  
113 in situ analysis of engravings in archaeological sites (Güth 2012), the analysis and  
114 reconstruction of coins and coin fragments in numismatics (Zambanini *et al.* 2009;  
115 Zambanini *et al.* 2008), and the capture of graffiti on Roman pottery (Montani 2012) are  
116 representative cases. More generally, the application of techniques for the automatic

117 recording and illustration of artifacts (Gilboa *et al.* 2013) could be applied to 3D cuneiform  
118 models, and used to streamline the process of documentation while removing one potential  
119 source of recording error. More specific techniques for the reconstruction of cuneiform  
120 tablets have been made in Ch'ng *et al.* 2013 and Lewis & Ch'ng 2012, which include the  
121 analysis of the complete tablet size as a template for fragment reconstruction, and the use of  
122 stigmergy as a model for interaction between users.

123 Furthermore, it is possible that many generalized algorithms could be adapted to select or  
124 orient particular fragments for reconstruction (Kleber & Sablatnig 2009). For example, the  
125 popularity of Optical Character Recognition (OCR) software has ensured that a number of  
126 language independent methods exist for recognizing the orientation of written data (Hochberg  
127 *et al.* 1995; Lu & Tan 2006), and it is probable that these can be adapted to suit the cuneiform  
128 text found on the tablets. Analysis of the fractal dimension (Wong *et al.* 2005) of an edge  
129 might also provide a useful index for sorting potentially matching edges.

130 The capture and visualization of fragments represents only one part of the virtual cuneiform  
131 reconstruction problem. Manipulation of fragments in virtual space is an issue that must be  
132 considered, and it is likely that initial tests with a virtual environment will give mixed results  
133 when users with variable experience engage with a 3D interface for the first time. Keehner  
134 (2006) and Vora *et al.* (2002) indicate that participation in virtual tasks has a positive learning  
135 effect, and dexterity will improve as interaction continues. Other issues, such as the lack of  
136 depth perception and haptic feedback are less easy to address. 3D visualization presents one  
137 possible avenue for investigation, as for example, stereo 3D has been shown to increase  
138 attention and offer a more natural interactive experience (Schild *et al.* 2012), but caution must  
139 be exercised because increased visual fatigue and even nausea may occur after prolonged use  
140 (Yu & Lee 2012). Newer gestural interfaces like the LeapMotion™ or Microsoft Kinect™  
141 may also be considered as novel methods for interaction, but at this time they lack sufficient  
142 resolution for stable manipulation of fragments. Electromechanical polymer screens (Kim *et al.*  
143 2013) and holographic haptic devices (Iwamoto *et al.* 2008) may in the future be able to  
144 provide tactile surface feedback to users. The detail of the matching surfaces of an artefact  
145 are usually so complex that anything less than a high resolution physical reproduction of the  
146 fragments such as those produced, for example, by the Creative Machines laboratory at  
147 Cornell University (Knapp *et al.* 2008) would be of limited value in the haptic sense.

148 The advances in related fields such as fresco reconstruction and pottery reconstruction  
149 suggest that the problems caused by virtual abstraction are not insurmountable, but in order to  
150 overcome them we must first investigate the interaction issues specific to cuneiform fragment  
151 reassembly.

## 152 **2. Materials and Methods**

153 With the exception of Ch'ng *et al.* (2013) which suggests that a solution to the problems  
154 associated with cuneiform reconstruction may exist in the field of complexity science, there is  
155 currently no published research specific to cuneiform reconstruction strategy. The first goal  
156 of the research presented here was to determine some of the basic techniques employed by

157 participants to match together and to discard clay fragments in both the real and virtual world.  
158 To achieve this, five sets of clay tablet fragments were scanned using a NextEngine HD 3D  
159 scanner. Each set contained between 6-8 fragments which were scanned in at medium  
160 resolution (at 2.5k sample points per inch), with each model containing approximately 1.5  
161 million vertices. The resulting models were decimated to reduce the vertex count to  
162 approximately 30 thousand vertices and were then imported into a custom made virtual 3D  
163 environment (Vizard based) configured to accept mouse and keyboard input to control the  
164 position and rotation of the fragments in virtual space. The application also supported  
165 stereoscopic 3D visualization using an interlaced field pattern and polarized glasses. A  
166 computer with an AMD Phenom II x4 955 processor, 8Gb of RAM, and an Nvidia GTX 560i  
167 graphics card was used for each test. A generic 105 key QWERTY keyboard and a 3 button  
168 optical mouse with scroll wheel were connected as input devices, and an LG Cinema 3D  
169 Monitor (D2342P) was used for both 2D and 3D output.

170 Pilot studies were carried out to determine appropriate time limits for reconstruction tasks in  
171 the virtual and physical environments during each experiment. From these pilot studies it was  
172 determined that a time limit of 12 minutes was appropriate for virtual tasks. After  
173 consideration from multiple sources (Bertaux 1981; Guest *et al.* 2006; Mason 2010; Martin  
174 1996; Nielsen & Landauer 1996; Schmettow 2012), it was decided that as the current study  
175 represented a precursor to a larger investigation and involved both qualitative and  
176 quantitative aspects, sufficient information to determine the direction of future work could be  
177 obtained with a relatively small number of participants. In total, 15 participants performed the  
178 experiments, 8 of which were male and 7 were female. The mean age of participants was 32  
179 years, with the youngest participant being aged 24 and the oldest age was 41. Each  
180 participant was isolated for the duration of the test in the Chowen Prototyping Hall at the  
181 University of Birmingham, and presented with a series of tasks involving three methods of  
182 interaction:

183 1. Physical reconstruction task

184 The participant was asked to reconstruct physical tablets from a collection or  
185 collections of fragments. Participants were informed at the beginning of each task that  
186 the collection of fragments they were presented with may be pieces from one tablet,  
187 more than one tablet, or may not fit together at all. The collections were sorted so that  
188 they contained the fragments of a complete tablet and either zero or more superfluous  
189 fragments. The purpose of this task was to provide baseline values for current  
190 reconstruction methods, and explore the effect of superfluous fragments on the  
191 manual reconstruction process.

192 2. Virtual reconstruction task

193 Participants were presented with the equivalent reconstruction tasks of physical  
194 participants, but were given virtual 3D fragments rather than their real-world  
195 counterparts.

## 196 3. Stereoscopic virtual reconstruction task

197 Participants were shown virtual fragments on a 3D monitor, and asked to perform the  
198 same reconstruction tasks as described above. This test restores a sense of depth  
199 perception to the participant, but still requires manipulation of 3D objects using  
200 standard input devices. This separates the effects of the lost depth perception from the  
201 effects of remote object manipulation using a keyboard and mouse.

202 Participants were also asked to reconstruct sets that contained either 2 superfluous fragments,  
203 or a number of superfluous fragments equal to the number of valid fragments (N) in the set.  
204 These tasks were referred to as N+2 and 2N respectively. In all cases, the time taken to  
205 complete the task and the accuracy of the completed tablet were recorded, as was the time to  
206 make the 1<sup>st</sup> and 2<sup>nd</sup> join. For virtual tasks, the physical operations (rotate, move) used to  
207 achieve the end result were recorded in a log of participant interactions during each test. At  
208 the completion of each task, the participant was asked a series of questions to elicit  
209 qualitative feedback. The environment used in the experiments was consistent, with physical  
210 surfaces coloured black to match the background colour of the screen used in the virtual  
211 tasks. Identical input and output devices were used for all virtual tasks, and instructions were  
212 provided in a script. Information about the controls for the virtual system were provided on a  
213 printed sheet next to the computer, which the participant was instructed to read before the test  
214 began. The sheet remained in place next to the computer for the duration of the experiment.

215 **3. Experimental Results**

216 All participants in the first test group were able to reconstruct the physical fragments into  
217 complete tablets well within the allotted time. The fastest join (*i.e.* the time to join the first  
218 two fragments together) was made within 5 seconds with the average time to the first join  
219 being 34.6 seconds. The average time between the first and second match was 33.8 seconds.  
220 The fastest participant completed the entire process within 65 seconds. No participant took  
221 more than 5 minutes and 49 seconds to reconstruct the tablet from the set of fragments that  
222 they were given.

223 The interaction methods employed by participants fell into two broad categories: *Methodical*  
224 and *Selective*. *Methodical* interactions involved a “brute-force” approach to the  
225 reconstruction process, comparing fragments systematically and then retaining those pieces  
226 that join together. *Selective* interactions were more discriminating, involving careful  
227 observation of the fragments before choosing those that were likely to form a cogent pair. It  
228 was observed that participants favoured a particular method of interaction, and did not tend to  
229 change their method. It was also observed that the manual manipulation of fragments was  
230 very free, with multiple simultaneous operations. It was not unusual for rotation and  
231 movement operations to be carried out in both hands at the same time. The initial freedom of  
232 motion became compromised as the number of fragments being held increased, so that  
233 participants were forced to discard the collections that they were holding in order to  
234 manipulate only relevant pieces. This became problematic as the reconstructed tablets neared  
235 completion. Several participants commented that glue or tape would have been helpful during

236 the reconstruction process. Contrarily, the deliberate exclusion of simulated gravity from the  
237 virtual environment means that holding fragments in position is not an issue, although some  
238 participants noted that a method of grouping individual fragments into a single object would  
239 have made manipulation easier. Unfortunately, the restrictions of a virtual interface using  
240 standard equipment currently prevent the fluid ambidextrous manipulation of multiple  
241 fragments. When using a keyboard and mouse, the participant is restricted to sequential  
242 actions on a single fragment, which in turn increases the time required to manipulate  
243 fragments into the desired position.

244 Performance in the virtual tasks was significantly lower than in the physical, with only one of  
245 the participants managing to reconstruct a complete tablet before the end of the 12 minute  
246 session. However, 11 of the 15 of participants were able to make at least one successful join,  
247 with the fastest participant taking 27 seconds to make a connection. Another participant had  
248 the shortest inter-match time (the time between a participant making the first and second  
249 join), taking just 33 seconds to find the second join.

250 With the sequential nature of virtual manipulation (where users are restricted by the interface  
251 into performing actions on only one fragment at a time), almost 75% of the actions carried  
252 out by the participant are rotations, which typically occur before a participant moves  
253 fragments together.

254 The participant interactions were classified so that participants who were able to make at least  
255 two matches in the virtual system were deemed to be *successful*, while those who made fewer  
256 than two joins were classed as *unsuccessful*. Successful participants typically rotated  
257 fragments less, with an average of approximately 72%, ranging between 56% and 83%`  
258 rotations. In contrast, 77% of the interactions made by unsuccessful participants were  
259 rotations, ranging between 70% and 92%

260 Figure 3 shows the rotation and translation events for a particular participant over the course  
261 of the experiment. The numerical identifier of the fragment being manipulated is expressed  
262 on the Y axis, with the time in seconds progressing along the X axis. The participant's actions  
263 shown in Figure 3 illustrate a heavy bias towards fragment rotation. These participants were  
264 unable to find any matches between the fragments, and ultimately stopped without making a  
265 single match. In comparison, Figure 4 shows the activity of more successful participants who  
266 made at least two joins from the provided set. These participants manoeuvred the fragments  
267 into close proximity after an initial inspection, and then continued to manipulate them until  
268 they were either matched or discarded.

269 If a participant aligns one fragment so that the edge appears to join with another fragment, the  
270 participant will move the fragments together and attempt a close fit. Pieces that do not match  
271 will typically be moved away from the target piece and discarded. This method of virtual  
272 reconstruction is reminiscent of the selective strategy employed by some participants in the  
273 manual reconstruction experiments. It is possible that the speed reduction encountered when  
274 using the virtual interface makes a brute-force, methodical approach to the joining process  
275 too laborious for users to focus on.

276 In common with physical strategy, 14 of the 15 participants began their digital reconstruction  
277 tasks by manipulating one of the larger fragments in the set, with 6 participants choosing the  
278 largest available fragment regardless of its position on screen. This mirrors observational  
279 evidence from the physical tests and also the feedback from several users on their individual  
280 reconstruction strategies.

281 The size of the first fragment chosen by the user did not directly affect the speed at which the  
282 participants made matches, although it may be useful to consider this preference for starting  
283 when designing a virtual system that can automatically suggest fragments to users. In the  
284 majority of these cases, the users will be looking for a smaller fragment than the one they  
285 currently hold.

286 Graphing the points of interaction within the virtual space reveals that unsuccessful  
287 participants (those who made fewer than two joins in the virtual system) were more likely to  
288 pull fragments towards the camera to enlarge them, while successful participants (those who  
289 made two or more joins in the virtual system) spent more time interacting with fragments at  
290 their original location. These interaction maps in Figures 5 and 6 show a front (XY) and side  
291 (ZY) view of the virtual space, with the areas of most activity being shaded darker. If we  
292 examine these graphs, we can see that the most noticeable clusters of activity are at depth 1 in  
293 the Z axis, which is the default starting position that fragments are placed on the screen.

294 This activity is present for both successful and unsuccessful participants. The graph of the  
295 unsuccessful participants also shows clusters of activity at depth 0 and at -0.5 which indicates  
296 that the fragments have been moved towards the camera. The disparity between the  
297 interactions of the successful and unsuccessful participants is more pronounced when viewed  
298 in 3D.

299 Figure 7 is a 3D representation of this spatial interaction information and shows the sparse  
300 interaction patterns of the unsuccessful participants, with isolated areas of activity towards  
301 the default fragment depth of 1 and the zero point of the graph. In contrast, the successful  
302 participants whose activities are illustrated in Figure 8 show a greater level of activity at the  
303 default fragment depth, whilst very little activity occurs in other areas of the virtual space.

304 As would be expected, the introduction of superfluous fragments appears to increase the time  
305 that participants need to make a match, with the minimum completion time increasing as the  
306 number of spurious fragments increases. This is reflected in the results from the physical  
307 tasks as shown in Figure 9.

## 308 **5. Discussion**

309 Participants revealed several key features that could be used to improve the virtual  
310 reconstruction process. Recurrent attributes identified by participants include the surface  
311 markings and colour of a fragment. The smoothness of fragment surface was also identified  
312 as allowing participants to distinguish sign areas and blank surface areas from obviously  
313 broken edges. Participants commented that the size of the fragments was important, with  
314 larger fragments being used as anchor points for testing smaller fragments against. This was

315 also shown in the analysis of the logs of initial interaction with fragment sizes from the  
316 virtual environment. Virtually pre-sorting larger collections of fragments by these features  
317 may improve efficiency of reconstruction. This technique has seen some success in the field  
318 of fresco reconstruction, and a virtual system to suggest fragments based on these features is  
319 the next logical step.

320 Many subjects stated that the lack of haptic (tactile) feedback was an issue during the virtual  
321 reconstruction process, and the lack of depth perception (leading to problems with object  
322 scaling) was also mentioned by multiple users. While the effect of depth perception was  
323 investigated during this study, the effect of haptic feedback and touch were less easy to test at  
324 this stage. A larger study has been planned to investigate the effectiveness of touch screen  
325 technology and explore several alternative techniques for interaction and visualization on  
326 static and mobile platforms.

327 It was assumed that the early performance of the participants in the virtual tasks would  
328 depend in part on their previous exposure to 3D software, and those participants with  
329 previous experience of 3D modelling and GIS software would be more comfortable  
330 manipulating objects in 3D space from the beginning. This proved not to be the case, which  
331 tallies with the results of other experiments and suggests that a longer exposure to the virtual  
332 interface over a course of multiple sessions would improve the performance of participants in  
333 the reconstruction tasks.

334 The 3D heatmaps reveal that the interactions of successful participants in perpendicular  
335 planes (i. e. in our experiments in planes parallel to the XYplane, see fig. 7) occur over a  
336 wider area than those of unsuccessful participants, while motion at different points on the Z-  
337 axis is less frequent. The interactions of unsuccessful participants exhibit a greater range of  
338 motion along the Z axis, with less overall motion in planes parallel to the X-Y plane. We see  
339 from this that successful participants make more use of the available X-Y screen space, with  
340 more activity occurring in the spaces between hotspots. In contrast, the unsuccessful  
341 participants have a much less energetic profile, with more separation in the Z axis. It is  
342 possible that the effect of perspective scaling is a contributing factor in the performance of  
343 these participants, with distant fragments being misinterpreted as smaller than they actually  
344 are.

345 Multiple participants commented that virtual reconstruction was more difficult because the  
346 depth of the fragments was indeterminate, and pieces that appeared to fit together were  
347 actually positioned at different depths, although this was not apparent on the 2D screen.  
348 While the use of binocular 3D subjectively increased the effectiveness of the virtual  
349 reconstruction environment, it produced no measurable positive effect to the reconstruction  
350 process, and had negative associations with the availability of the technology and the  
351 increased eye fatigue caused by convergence/fixed-focus. One participant was unable to work  
352 with the 3D screen despite having no binocular vision defects. Several participants claimed to  
353 feel more able to perform the task when working with stereoscopic 3D models, but ultimately  
354 performed no better than those working with normal screens. In measured terms, fewer

355 participants were able to make a second join when using stereoscopic 3D within the allotted  
356 time, but overall their performance was on par with participants working without stereoscopic  
357 glasses.

358

359 Participants also stated that the lack of tactile feedback was a significant drawback for virtual  
360 reconstruction. While it may currently be impossible to implement accurate tactile feedback  
361 within the virtual system, it is possible that additive manufacturing techniques could be used  
362 to provide a physical copy of fragments that appear to join in the virtual system. These  
363 printed fragments could then be used to make a definitive decision on the validity of a  
364 proposed join. More extensive use of additive printing technology could also be considered  
365 so that staff with limited training can carry out multiple fitting operations concurrently.  
366 Replica parts are low value and replaceable, having no special handling requirements or  
367 storage considerations.

## 368 **6. Concluding Remarks**

369 In the course of our experiments, we observed several behaviours that could improve the  
370 virtual reconstruction process for cuneiform fragments. Firstly, we observed that more  
371 successful participants kept fragments close to each other in the Z axis, and as such a visual  
372 representation of Z depth within the workspace may help to help participants to perform  
373 better. However, we observed that restoring depth perception by stereographic representation  
374 does not improve participant performance. We have also observed that participants tend to  
375 begin with a larger fragment, with which they then try to match with smaller fragments. In a  
376 virtual system that automatically suggests possible matches, a bias toward suggesting smaller  
377 fragments than the one currently held may also improve the participant's performance. The  
378 absence of tactile feedback was noted by several users, and while no technology currently  
379 exists to completely restore the sense of tactility, it may be possible to provide an audio or  
380 visual feedback system that provides feedback on the closeness of fit between multiple  
381 fragments. One example of such a system might be a border around the visible fragment that  
382 becomes more opaque as the closeness of fit between the fragments increases. Other features  
383 that could improve the experience for participants working within a virtual system include the  
384 ability to glue multiple fragments together so that they can be manipulated as a single object,  
385 and the ability to magnify fragments so that close inspection of edges can be carried out  
386 quickly. The results of our experiments indicate that the manual reconstruction of fragments  
387 is faster than virtual reconstruction, but the physical world does not allow for easy parallel  
388 processing of fragment sets, nor does it permit casual accessibility. Despite the limitations of  
389 a virtual system, the potential for task parallelization and human computation makes virtual  
390 reconstruction an attractive choice for fragment joining.

391 Crowdsourcing projects like the Galaxy Zoo (<http://www.galaxyzoo.org/>) which use human  
392 volunteers to classify new images of galaxies, and Cellslider  
393 (<https://www.zooniverse.org/project/cellslicer>) which uses a similar framework to identify  
394 potentially cancerous cells, provide a platform for the classification of scientific images that

395 computers are currently unable to match. These projects show how crowdsourcing can be  
 396 used successfully for human computation, with existing tools being able to connect potential  
 397 participants with researchers for free (<http://www.zooniverse.org>,  
 398 <http://www.crowdcurio.com>). Other services like Amazon's Mechanical Turk  
 399 (<http://www.mturk.com/mturk/>) provide a framework for participants to bid and work on a  
 400 variety of projects in exchange for money. The success of these projects suggests another  
 401 potential method for the reconstruction of artefacts, with a virtual environment providing an  
 402 interface for paid or voluntary human workers. If the ethical considerations of wages  
 403 estimated in the range of US\$ 1.25 per hour for Mechanical Turk (Ross *et al.* 2010), the lack  
 404 of worker's rights (Fort *et al.* 2011), and potential security concerns can be avoided, the  
 405 potential power of crowdsourcing is difficult to dismiss.

406 A distributed system designed to maximize the advantages of the virtual environment whilst  
 407 minimizing the inherent limitations could open up the field of cuneiform reconstruction to  
 408 new audiences, and free scholars from the drudgery of manual reconstruction. It is also likely  
 409 that the research behind such a system would be applicable to a number of other fields within  
 410 the archaeological community.

#### 411 *7. Acknowledgements*

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 414 Heritage and Cultural Learning Hub at the University of Birmingham.**8. References**

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Illustration 1: Screenshot showing virtual reconstruction task on the left, in contrast to a physical reconstruction task on the right.

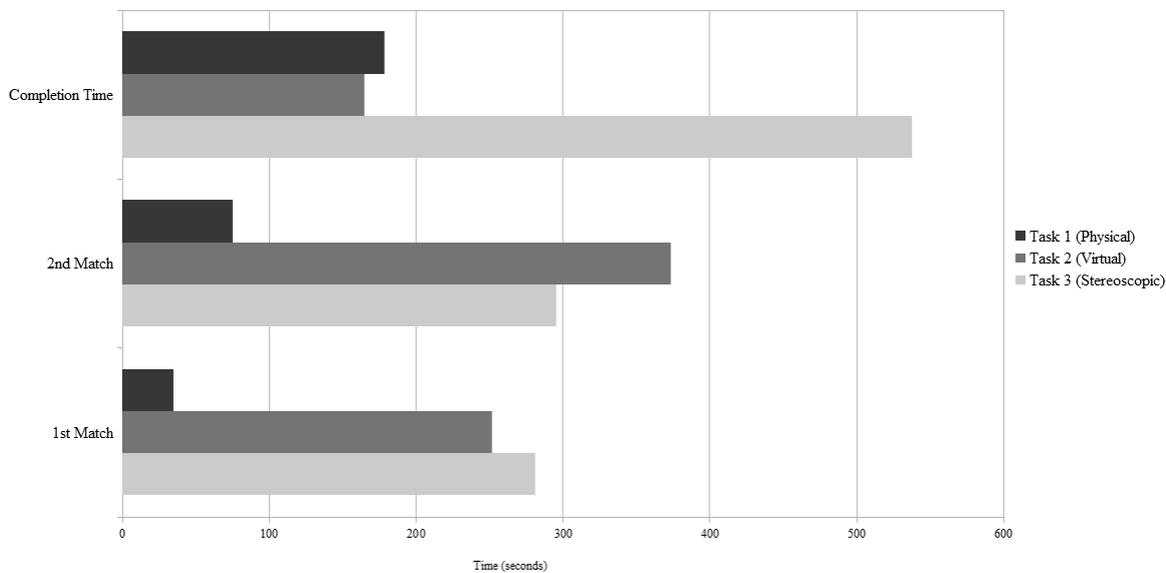


Figure 1: Graph showing the mean 1<sup>st</sup> match, 2<sup>nd</sup> match and completion time for each task.

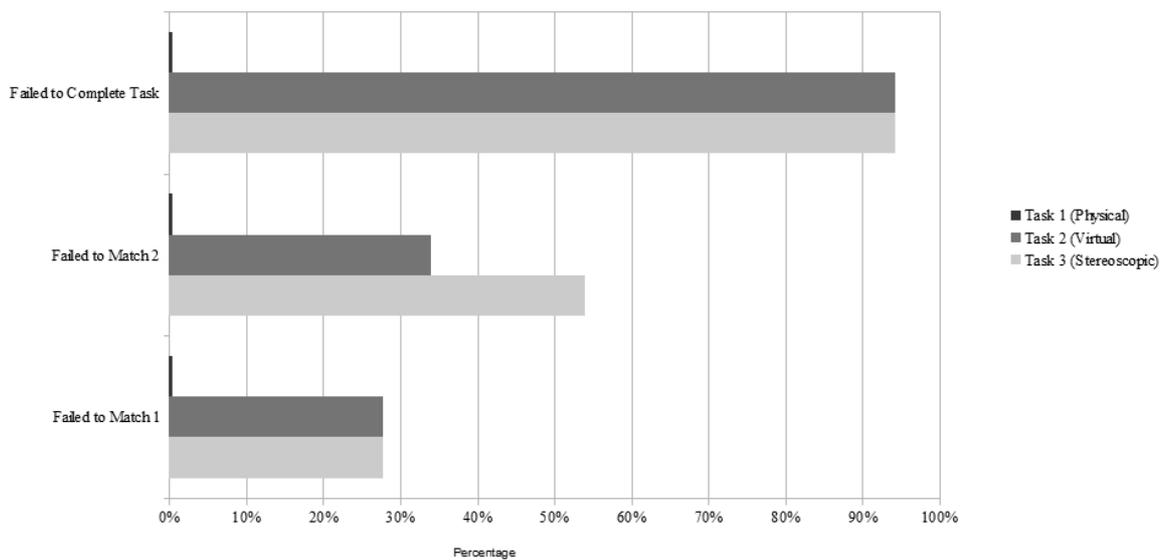


Figure 2: Graph showing percentage of participants unable to reach experimental milestones for each task.

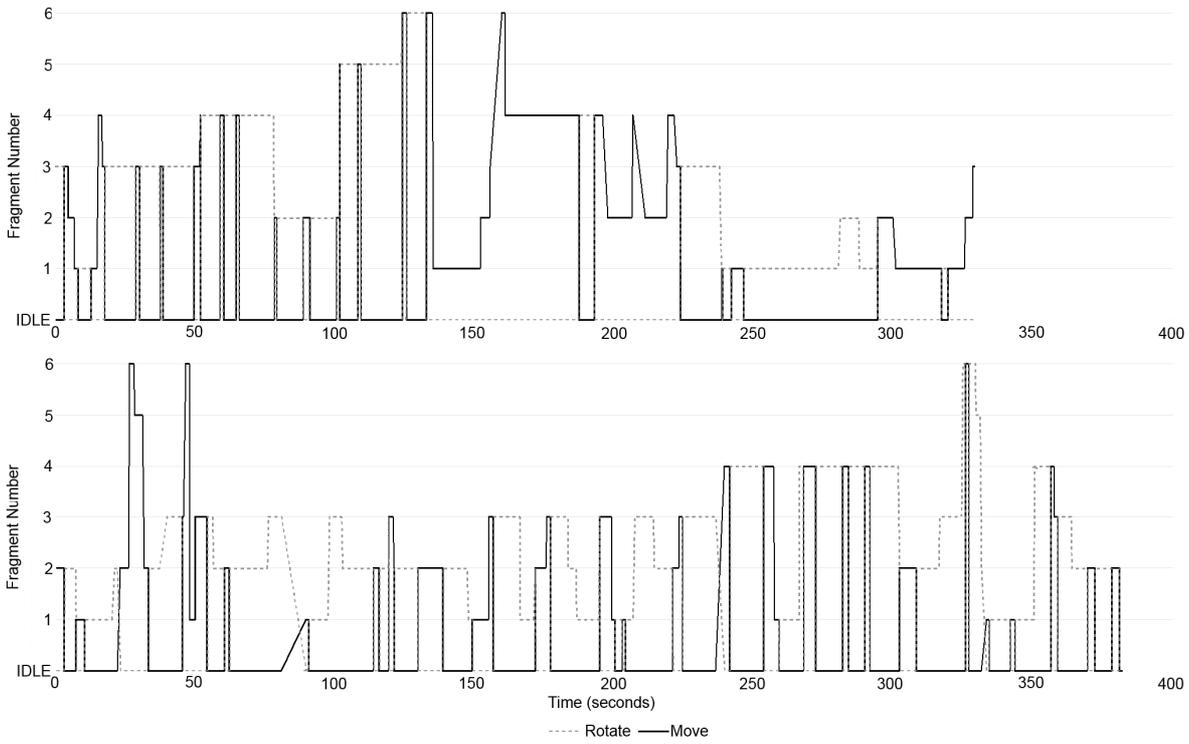


Figure 3: Graph showing the rotation and movement actions of unsuccessful participants when using the virtual reconstruction system.

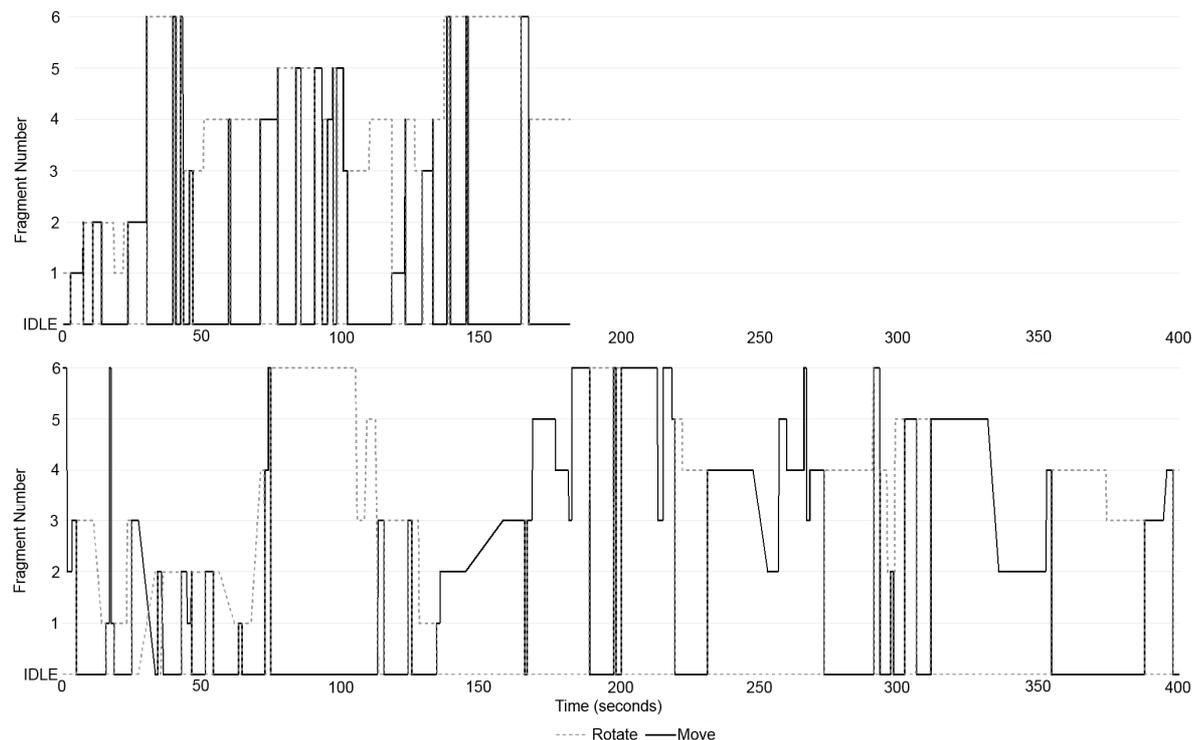


Figure 4: Graph showing the rotation and movement actions of successful participants when using the virtual reconstruction system.

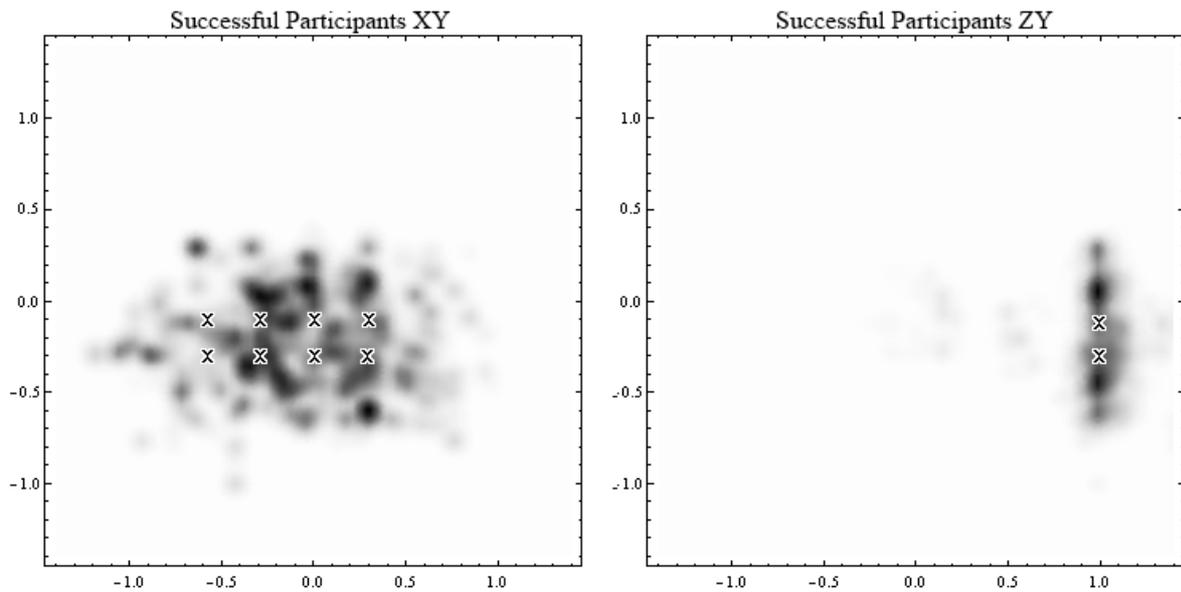


Figure 5: Interaction map showing the average frequency of fragment interaction in 3D space for successful participants. The left hand graph represents a "screen view", whilst the right hand graph shows the depth of fragments within the space. Crosses indicate the starting position of fragments.

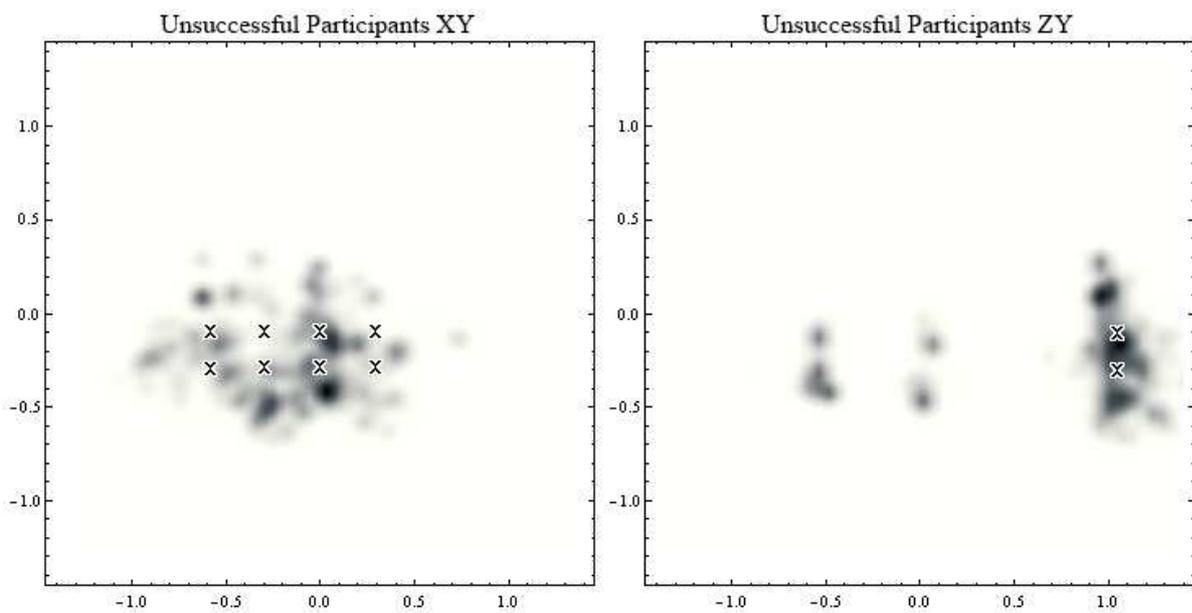


Figure 6: Interaction map showing the average frequency of fragment interaction in 3D space for unsuccessful participants. The left hand graph represents a "screen view", whilst the right hand graph shows the depth of fragments within the space. Crosses indicate the starting position of fragments.

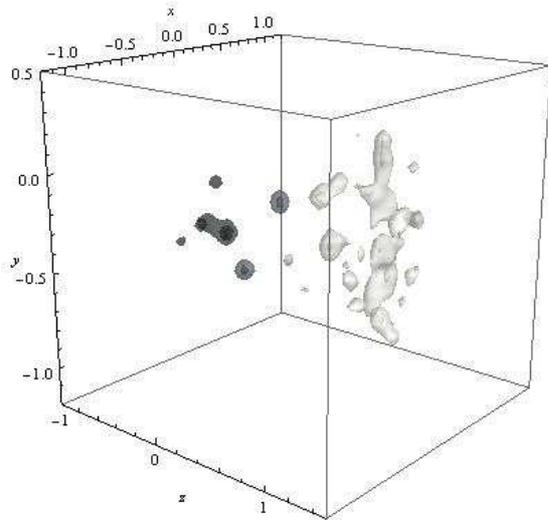


Figure 7: Graph showing the interaction patterns of unsuccessful participants in the virtual space.

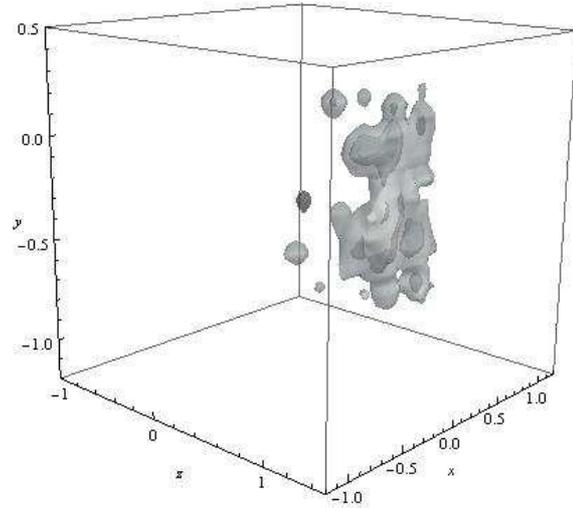


Figure 8: Graph showing the interaction patterns of successful participants in the virtual space.

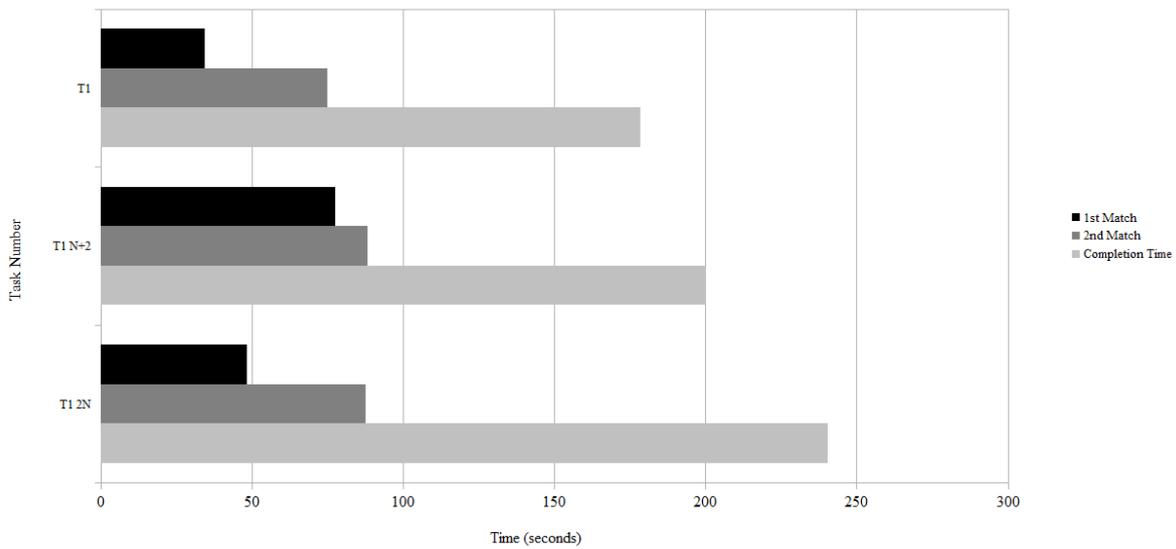


Figure 9: The effect of additional fragments on reconstruction time for participants in task 1.

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