Journal of Engineering Design

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cjen20

Effects of activity time limitation on gesture elicitation for form creation

Tijana Vuletic, Chris McTeague, Gerard Campbell, Laura Hay & Madeleine Grealy

To cite this article: Tijana Vuletic, Chris McTeague, Gerard Campbell, Laura Hay & Madeleine Grealy (2023) Effects of activity time limitation on gesture elicitation for form creation, Journal of Engineering Design, 34:11, 963-985, DOI: 10.1080/09544828.2023.2271773

To link to this article: https://doi.org/10.1080/09544828.2023.2271773

Published online: 09 Nov 2023.

JOURNAL OF ENGINEERING DESIGN
2023, VOL. 34, NO. 11, 963–985
https://doi.org/10.1080/09544828.2023.2271773

Effects of activity time limitation on gesture elicitation for form creation

Tijana Vuletic [a,b], Chris McTeague[a,c], Gerard Campbell[a,d], Laura Hay [a] and Madeleine Grealy[d]

[a]Department of Design Manufacture Engineering Management, University of Strathclyde, Glasgow, UK; [b]James Watt School of Engineering, University of Glasgow, Glasgow, UK; [c]TUM School of Engineering and Design, Technical University of Munich, Munich, Germany; [d]Glasgow School of Psychological Sciences & Health, University of Strathclyde, Glasgow, UK

ABSTRACT

Cognitive processing employed during design includes both time critical and time-consuming types of thinking. The ability to match the pace of design generation or modification with the designers thinking processes can be particularly important with gesture-based interfaces for form creation, especially where representation modes of input and response may influence the choice of activities performed. Particularly in gesture elicitation studies, time-consuming design activities can shift the focus on forming the analogies between problem at hand and prior knowledge and experiences, rather than intuitive gesture suggestions that would be the best fit for the given representation mode. However, design methodologies do not prescribe or discuss time limitations and their use in this context. In this paper, time limitation is explored during a gesture elicitation study for three-dimensional object creation, modification and manipulation, by comparing two study parts, one where time limitation was imposed and one where time was unlimited. Resulting gesture durations in both parts were comparable and elicited gestures were similar in nature and employing same elements of hand motion, supporting the hypothesis that time limitation can be a useful methodological approach when gestures are used for interaction with 3D objects and representation and interaction modalities are matched.

ARTICLE HISTORY
Received 7 July 2023
Accepted 12 October 2023

KEYWORDS
Conceptual design; gesture interaction; form creation; timing; CAD

Introduction

Early instances of gesture use in interaction interfaces occurred in the 1980s. Gestures were used for an interaction with a display (Bolt 1980) and a three-dimensional (3D) object manipulation in virtual reality (VR) environment (Zimmerman et al. 1986). More consistent development of gesture-based interfaces continued from early 1990s to early 2000s with applications designed for activities like robot control (Pook and Ballard 1996), Computer-Aided Design (CAD) interaction (Chu, Dani, and Gadh 1997), manipulation of 3D objects

CONTACT Tijana Vuletic tijana.vuletic@glasgow.ac.uk James Watt School of Engineering, University of Glasgow, James Watt South Building, Glasgow G12 8QQ, UK

(O'Hagan, Zelinsky, and Rougeaux 2002) and navigation/selection in an application (Baudel and Beaudouin-Lafon 1993; Wilson and Oliver 2003). At times technological or computational advances led to testing of ability they had for gesture recognition without a specific application being determined (Huang, Zhou, and Liu 2014; Liu, Wang, and Yan 2018). Early applications often used wearables, usually gloves, which provided good accuracy but encumbered the users and sometimes limited the breadth of motion. Sensing devices like depth cameras became more affordable and more accurate around 2010, and this led to a substantial rise of interest in gesture-based interfaces in a wide range of fields, offering ability to support 3D modelling (Arroyave-Tobón, Osorio-Gómez, and Cardona-McCormick 2015; Buchmann et al. 2004; Huang, Jaiswal, and Rai 2019; Matsumaru and Morikawa 2020; Ramani 2015; Robinson et al. 2007), assistive applications (Bhuiyan and Picking 2011; Ojeda-Castelo et al. 2018; Rodrigues, Carreira, and Gonçalves 2014), data input/authentication (Amma, Georgi, and Schultz 2014; Cha and Maier 2012; Guerra-Casanova et al. 2012; Lee et al. 2020; O'Connor et al. 2017; Trigueiros, Ribeiro, and Reis 2015; Yamada et al. 2014), manipulation/navigation in different contexts that require 3D representation (Alvarez-Santos et al. 2014; Hernoux and Christmann 2015; Hürst and Van Wezel 2013; Jacob and Wachs 2014; Liu, Zhang, and Li 2020; Lopes et al. 2017) and touchless control (Cicirelli et al. 2015; Salman et al. 2020; Santos et al. 2016; Walker et al. 2023; Wu, Wang, and Zhang 2016; Yeo, Lee, and Lim 2015; Zengeler, Kopinski, and Handmann 2018). For example, a surgeon could consult 3D scans during a procedure, rotate, zoom in, mark up, using touchless gestures while avoiding contamination of hands (Jacob and Wachs 2014; Lopes et al. 2017). Operators could control a robot remotely allowing its placement in a location that may be hazardous for an operator otherwise (Salman et al. 2020; Walker et al. 2023). Data could be inputted into a computer system using sign language (Trigueiros, Ribeiro, and Reis 2015). Designers could use hand gestures to create irregular shapes difficult or time-consuming to create and navigate using a mouse and keyboard (Matsumaru and Morikawa 2020; Ramani 2015).

Gestures for form creation

Applications of hand gestures for design activity occurred often, as they were deemed to have potential to aid creation of more intuitive interfaces able to interact with the form in a manner fit for its 3D representation. To ensure that future interaction between a designer and a system used for form creation provides required functionality, it was established that such system should provide:

- Ability to generate forms quickly and modify them throughout the design process, as ideas about design change (Alcaide-Marzal et al. 2013; Company et al. 2009)
- Intuitive modes of interaction based on natural human actions (Esquivel et al. 2014; Shankar and Rai 2014)
- Ability to focus on design requirements rather than interface use (Huang, Jaiswal, and Rai 2019)
- Representation means that are in harmony with the speed of ideation (Vidal and Mulet 2006; Cash and Maier 2021)
- Reduced cognitive load (Huang 2007).

Hand gestures (referred to as 'gestures' in the remainder of this paper) hold potential to address these requirements, if successfully implemented in the design interfaces.

While gestures are typically used because they are an intuitive and natural mode of human interaction, using them in contexts where they are currently not habitually used, and often limited by technological capabilities of the tools used for gesture recognition, means that a decision needs to be made on which gestures will be recognised. When these interfaces were created, system evaluation often focused on evaluation of the technical usability, and not the appropriateness of the gestures for the chosen activities (Vuletic et al. 2019). 3D modelling applications typically enabled designers to use free-form gestures to create splines or surfaces forming a 3D model (Arroyave-Tobón, Osorio-Gómez, and Cardona-McCormick 2015; Buchmann et al. 2004; Chu, Dani, and Gadh 1997; Han and Han 2014; Holz and Wilson 2011; Kim et al. 2005; Matsumaru and Morikawa 2020; Robinson et al. 2007; Vinayak et al. 2013; Vinayak and Ramani 2015), but required use of simple prescribed gestures to trigger predefined activities, e.g. pinch or grab to select an object. Vast majority of interfaces used predefined prescribed gestures, often chosen by the researchers developing the systems. In general, specific gestures used were often chosen because they were similar to activities performed in current interaction interfaces or because they were easily recognisable using technologies currently available to the researchers (Schmidt 2015). It was argued that there was a need to identify the most appropriate hand gestures for application in design interfaces (Huang, Jaiswal, and Rai 2019). Researchers have also found that personalisation of gestures was preferred (Kela et al. 2006). The incorporation of user sourced gestures was also found to be beneficial, as those gestures were found to be 'guessable' – easier to anticipate or remember (Nacenta et al. 2013; Wobbrock et al. 2005).

Design needs and elicitation challenges

More recent exploration of gestures for form creation tends to elicit the gestures from a pool of representative users to ensure they are easy to learn and appropriate for the activities. In the wider field of Human–Computer Interfaces (HCI) in-air user-based gesture elicitation was used to build vocabularies of gestures for AR environments (Piumsomboon et al. 2013), TV control (Dong, Figueroa and El Saddik 2015; Dim et al. 2016; Esquivel et al. 2014), descriptive mid-air interactions (Jahani and Kavakli 2018) and 3D CAD modelling in conceptual design (Khan and Tunçer 2019). These studies used the user-based gesture elicitation approach established by Wobbrock and Morris (Morris, O Wobbrock, and Wilson 2010; Vatavu and Wobbrock 2015; Wobbrock, Morris, and Wilson 2009) that focuses on building a user-sourced vocabulary of gestures through the classification of individual gestures and calculation of agreement rates between the participants. This approach aims to identify gestures that are fit for use in a specific context and easy for users to learn or guess, as they were elicited from groups of users with certain common characteristics. Sole use of agreement rate for gesture inclusion decisions was questioned in the HCI research community, and proposition was made to supplement it by metrics measuring significance of findings such as Fleiss κ (Tsandilas 2018). Comparisons of the observed frequencies in the data with the frequencies expected to occur by chance using Pearson's Chi Square test of Fisher's exact test are also used, and choice of the test depends on the size of the sample (Pons and Jaen 2020; Vatavu and Wobbrock 2016). Newer research suggests that perhaps gesture choice should be viewed as a computational optimisation problem (Tsandilas and Dragicevic 2022).

While user-based gesture elicitation increases the intuitiveness and appropriateness of chosen gestures, it can also have potentially negative influences. Users' prior experience with the technologies used in the elicitation study or similar technologies used in their work or life can lead to legacy bias (Morris et al. 2014). For example, even if the users are asked to interact with three-dimensional object on a computer screen, the similarity between visual representation on a 2D screen and the phone screens they see daily may lead them to apply interaction paradigms used for the phone interaction to proposed gestures, e.g. participants are sometimes using pinch gesture to zoom in/out. Often general public is used instead of specialists in a specific field to remove the narrow professional bias and make the gestures more easily generalisable for the wider audiences (Wobbrock, Morris, and Wilson 2009).

During the process of designing a study to elicit most appropriate hand gestures for form creation during product design, the authors of this paper wondered if lack of time limitation for gesture performance would allow the participants ample time to diverge from their instinctive reactions and generate proposed activities through comparisons with paradigms used for the creation of solid shapes in a CAD system or even drawing using pen and paper instead of using hands in a 3D environment.

Types of thinking during three-dimensional form creation

The ability to match the pace of design generation or modification to the designers' thinking processes can be more important for the effectiveness of a design process than the focus on detail of the design (Fuge et al. 2012). Bounded ideation is one of the processes that can negatively influence it and occurs when designers' focus is diverted from thinking about the ideation and form creation to thinking about commands and procedures used in tools that enable the designers to create that form (C.-C.S. Huang 2007; Robertson and Radcliffe 2009; Robertson, Walther, and Radcliffe 2007). However, majority of digital tools used during design creation require the participants to think of strategies or steps they will take to create an object while they are also thinking of the design form itself. Dual process theory established by Evans and Stanovich (2013) could potentially contribute to the understanding of difficulties designers encounter while generating 3D forms by using tools such as mouse and a keyboard to visualise them on a 2D computer screen. Dual-process theory proposed that there are at least two major types of cognitive processes present in design: those that are intuitive and associated with rapid responses, named Type 1, and those that are analytical, deliberate and slow used during analysis and reflection, named Type 2 (Evans and Stanovich 2013). They act in conjunction across the design task as a whole, but each is likely to be dominant in a specific phase of a design activity (Cash and Maier 2021). It is believed that when representation mode of an input and response are matched Type 1 processing occurs, as the brain does not need to translate between different types of representations and can instead focus on the task at hand. This type of processing is typically quicker and could in practice be characterised by shorter activity duration. When representation modes are mismatched, Type 2 processing is required to interpret and manipulate the input and could be characterised by longer activity duration (Evans and Stanovich 2013). Dual process theory is just beginning to be established in the design field (Cash et al. 2019) and its methodological application presently relies on coding data collected during a design activity, interpretation of the results by the researchers that are used as a basis for model building or drawing conclusions about the design process. One area of application explored was the idea generation process and what dual-process theory might mean for it (Gonçalves and Cash 2021; Moore, Sauder, and Jin 2014).

Use of time limitations and the relationship between timing and types of thinking undertaken during design activities

Dual process theory combined with legacy bias that may be encouraged if unlimited time was allowed for gesture elicitation, inspired design of a study reported in this paper. The nature of input and response are matched (in-air 3D shape creation), aiming to allow for a comparison of a stage that has no time limitation and a stage that imposes a time limitation, duration of which was expected to allow effective gesture proposition and at the same time reduce overthinking. The activities are unrestricted in terms of gestures participants can propose, but the experiment environment is designed in a manner that aims to encourage elicitation of intuitive responses, rather than allow creation of analogies with known concepts. The hypothesis is that unrestricted time given to a participant when proposing a gesture which is expected to lead to a more detailed and more appropriate gesture suggestion may instead lead to deliberate analysis and reflection and possibly provide a gesture proposition based on an analogy with a known concept rather than one that is the most appropriate. In contrast, time restrictions imposed on the activity, may force the participants to provide their instinctive reaction without overthinking. Underlying thinking processes that are quick and intuitive were believed to be the most appropriate for the activities employed in the study this paper focuses on, and a good match for thinking processes and pace of 3D form creation. Time required for gesture preparation i.e. consideration and selection of the most appropriate gesture for the activity, could tell us if participants are trying to create analogies with known paradigms. Time required for gesture performance, i.e. actual physical interpretation of the gesture, could tell us about the match between thinking process employed and representation type. If preparation time is longer in the unrestricted stage than in the restricted stage that could indicate that participants are not proposing them instinctively but possibly trying to form analogies with their prior knowledge or experiences. If gestures proposed do not match the representation mode, the time it took to perform them would be longer in the stage with unrestricted time than in that with restricted time. When the performed gestures match the representation mode, then the time it took to propose them in the unrestricted stage would be expected to be shorter.

Findings from this study could enable a provision of recommendations for study design, if the focus of the study is user elicited gestures in a 3D space that require intuitive feedback and are as such sometimes difficult to methodologically design in a way that would allow comparisons with similar studies. This can mean that it is difficult to assess the significance and value of the contribution of these studies, as objectively evaluating the methods used in them and how they affected the findings is not an easy task. Particularly, looking at gesture-based studies, this difficulty appears in many aspects of design studies (Villarreal-Narvaez et al. 2020), for example classification methods and statistical analysis applied to resulting data (Tsandilas 2018; Vatavu and Wobbrock 2022), etc. The use of time limitations for activities used in design studies is an aspect that is rarely discussed, but that could methodologically have a significant influence on the findings. This paper is focusing on time limitations during gesture-based studies in a 3D environment, as this is the topic for which there were no recommendations given in the field. More specifically, if limiting the time allotted to a gesture correlated with a specific activity and if providing unlimited time would result in different gestures or different durations of gesture performance.

Design studies often suffer from a lack of methodological guidelines and standardised techniques that may improve their robustness and enable comparability between different studies. There is an ongoing discussion regarding how reliable, justifiable, generalisable and repeatable results can be achieved in design science (P.J. Cash 2018). The lack of standardisation is partially due to the breadth of topics studies cover, as some flexibility with methods is needed to reach specific goals in a divergent field of design research. Work reported in this paper is significant as it will contribute to the standardisation of the consideration of the time component, during the design of studies focusing on user elicited 3D gestures in particular. It is not aiming to provide a definitive guidance for all future studies, but instead start the conversation on the topic, and hopefully inspire others in the field to contribute their findings.

Context of the study reported in this paper

Study reported in this paper was an extension of a larger gesture elicitation study performed to explore if there was agreement between participants on proposed gestures for a variety of activities employed during 3D form creation (published in Vuletic et al. (2021)). The goal of a larger study was to collect the data that will eventually lead to a provision of an alternative modality of interaction that was not reliant on a specific technology. Currently CAD (Computer Aided Design) systems cannot provide adequate support for the manipulation of graphical data for form creation that would allow a virtually unlimited design space designers would have if physically sketching or modelling (Alcaide-Marzal et al. 2013; Shesh and Chen 2004). Compounding of the two studies meant that there were a few decisions made in study design that allowed for the collection of data about gestures, such as the choice of the objects and sequencing of activities, that were not relevant to the discussion about timing of activities for gesture elicitation and will not be discussed in this paper. The use of Wizard of Oz approach to allow for more immersive experience was considered, but ultimately rejected as it was deemed that it would introduce unwanted response times that may negatively interact with the intuitive responses.

Method

This study explores the time it took participants to prepare for the hand gesture performance, referred to as gesture preparation time in the remainder of the paper, and the time it took them to perform the gestures, referred to as gesture performance time in the remainder of this paper. Requirement for approval was waived by the institutional ethics committee, as the activities were deemed appropriate.

Participants in the study were placed in front of a screen displaying shapes they were asked to create or manipulate using their hands, and their responses were recorded using

Figure 1. The screenshot of one of the participants taking part in the study (front view on the left, side view on the right).

two cameras placed under the screen in front of the participant and to the left of the participant (see Figure 1 for views captured). There were 44 participants (29 male, 15 female), product design engineering students in their penultimate and final year of studies, or recent graduates. 'Mature' students were chosen as they can be considered advanced beginners or novice designers (Liikkanen and Perttula 2009), as they have the key characteristics of designers but have not fully adopted all established design workflows yet. On average they had 4.9 years of CAD experience (a mix of Solidworks, Creo, Inventor, Catia, Revit, Sketchup, Rhino, AutoCAD, Smartplant3D, Edgecam NX9, ProEngineer, Alias) and 1.4 years of design experience in the professional environment, including internships. Typically, they have spent at least 3 years working on student projects, and at least one of their projects had industry involvement, but they were not embedded in the company and instead worked as consultants. They have displayed the spatial perceptions skills, creativity and concept manipulation throughout their training. This made them a good compromise between experienced designers that would likely bring influence of previous experience (Piumsomboon et al. 2013) and general public that may not be able to tackle conceptual design problems which are niche and require a certain level of creativity and mental manipulation of vague concepts. The mix of capabilities design students possessed ensured data collected is representative of designer skills and needs. In addition to experiential data, information on dexterity was collected. Seven participants were left-handed, 33 right-handed and one participant was ambidextrous.

The study had two parts, illustrated in Figure 2.

In the first part, both gesture preparation time and gesture performance time were limited to 3 seconds. Three second limit was chosen by observing the designers while using CAD systems, and concluding that 3 seconds was at the higher range of the time it took to perform basic design activities for manipulation (zoom in/out, translate, etc.) and creation (e.g. draw a circle, extrude a profile) of 3D forms. In the second part, time was unlimited.

In Part 1, participants viewed the activity they would be asked to perform twice. Each viewing lasted 3 seconds and it was repeated twice to ensure the participants had a good grasp of it. Then they were given 3 seconds to think of a hand gesture to perform (gesture preparation time), and when the activity was shown for the third time, the participants were asked to perform hand gestures pretending that they were causing the activity (gesture performance time). Gesture performance time was also limited to 3 seconds, but for some

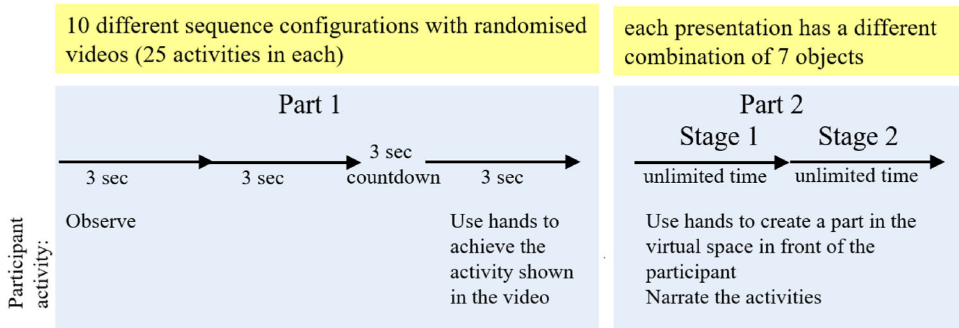

Figure 2. Visualisation of the study stages.

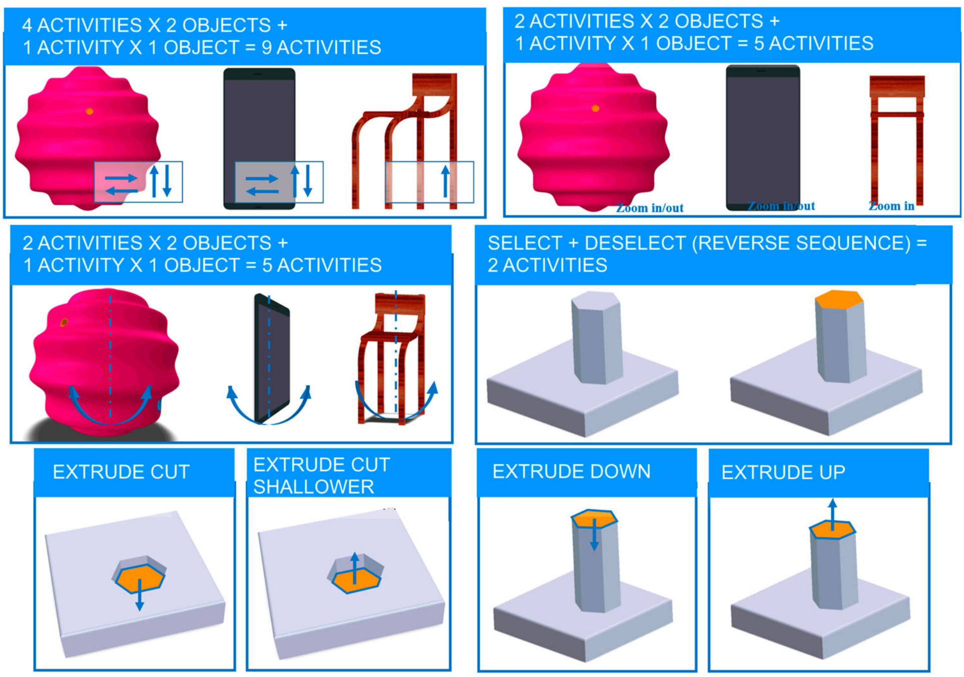

Figure 3. Objects and activities for Part 1 of the study.

activities it was shorter as it depended on the time it took to visualise a specific activity. However, it was never more than 3 seconds.

Activities and objects those activities were performed on are illustrated in Figure 3. Activities performed were translation in four different directions, zoom in/out, and rotate left and right for three different objects (3D models of an irregular sphere, a mobile phone, and a chair), selection and deselection of a top surface of a predefined console, extrude-cutting a hexagonal pocket from a rectangular block, reducing the depth of a pre-cut hexagonal pocket, and extruding the console up and down.

Other than the instruction to use their hands as if they were causing the activity, the participants were not given any additional information. Some asked about the nature of

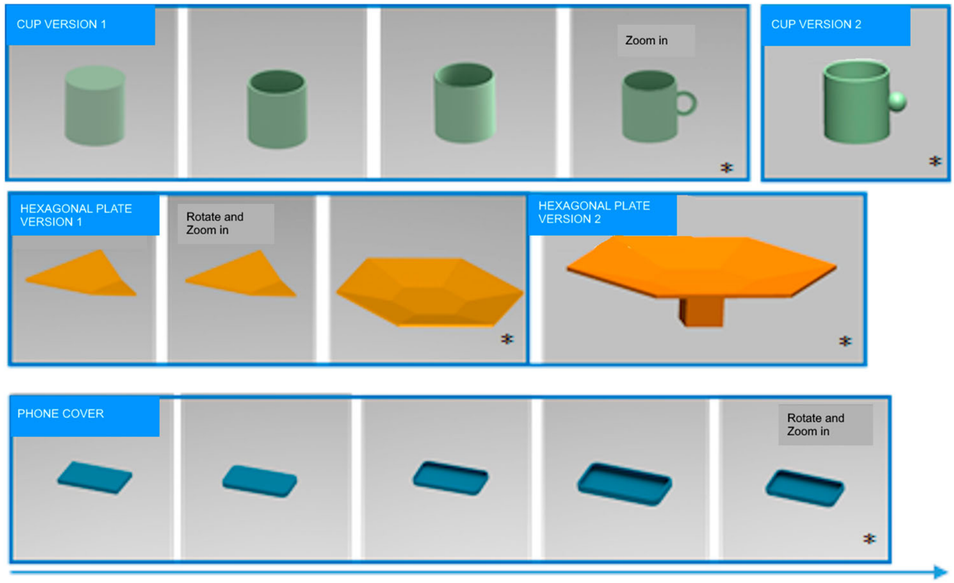

Figure 4. Objects for Stages 1 and 2 in the Part 2 of the study (Stage 2 objects are denoted with *).

the objects ('should I imagine that this is on the table?') and the response would be that whatever the object appears like to them was the accurate way to perceive it.

In Part 2, there were no time limitations, and participants were shown images of objects they were asked to create. Part 2 had two stages that had different levels of guidance embedded, Stage 1 was partially guided and Stage 2 was unguided. This was done to ensure that enough data is collected even if some participants skip a number of steps in the unguided Stage 2. In Stage 1, participants were shown images at different stages of completion, shown in Figure 4, and asked to propose how they would create the form shown in each of the steps. For two versions of a cup, the sequence had four steps, for two versions of a hexagonal plate the sequence had three steps, and for the phone cover creation the sequence had five steps. In Stage 2, participants were shown the complete object (objects with * shown in Figure 4) and asked to create it from scratch, with no intermediary steps given.

In Part 2, the participants were given additional instructions that they were to imagine they were creating a shape in a 3D environment in front of them, and that it does not have weight. They were free to perform hand motions they found the most appropriate. Timing of gestures was not mentioned.

Half of the participants performed the two parts of the study in reverse, to reduce the influence a time limitation in the first part of the study could have on the second part of the study, as there were concerns that the participants would unconsciously learn to impose a time limitation to the second part. This could have been avoided by using different participants in two parts of the studies, but that approach would introduce a more diverse cohort of participants instead. It was decided to accept the possibility of some percentage of the participants being influenced by time limitations and review the data for it so that the ability to compare reactions of same participants across both parts of the study could be retained.

To ascertain if the time allotted to the activity had an effect on the outcome, first the time it took to prepare for gesture and then perform it in Part 2 of the study was compared to 3 seconds allotted to each activity in the Part 1. If the time taken to prepare for the gestures (decide what gestures to perform) and perform the gestures in Part 2 was comparable to the 3 seconds defined in Part 1, then it was likely that for tasks requiring intuitive and fast responses time limitation could aid gesture elicitation process by pushing participants towards intuitive responses rather than creation of analogies with previous experience.

Second comparison was made between time required for gesture performance in Part 2 where it was unlimited, and up to 3 seconds assigned to gesture performance in Part 1. Short time for physical interpretation of the gesture could indicate that there was a match between thinking process employed and representation type, i.e. in-air free gestures fit well with the 3D nature of the imagined objects.

Third comparison was between the gestures elicited from both parts of the study, and it is an underlying condition for the interpretation of the first two comparisons. If the same types of gestures were elicited for the same activities in both parts of the study, then it can be concluded that the time limitation is not likely to negatively affect the gesture elicitation process by changing the nature of the gestures performed due to the limitation.

Results

Out of 44 participants, 43 were recorded due to camera failure for participant number 4. In Part 1, 1083 gestures were recorded; in Part 2, 702 gestures were recorded. Although the participants had unlimited time to prepare for and perform the gestures in Part 2, majority prepared for and performed the gestures within the time scales comparable to the 3 seconds chosen as a limitation in the Part 1 of the study. One participant took to 40s to prepare for a group of gestures, one took 46s to perform and explain the performance of specific gestures, however, these were the outliers. The gestures themselves were of the same nature and there were repetitions of the same gestures across both parts of the study. More detail on both of these topics will be given in the following sections.

Elapsed time for gesture preparation and gesture performance

Table 1 shows that up to 95% of gestures for the preparation and performance of gestures took less than 6 seconds, with 78.2% of gesture preparations taking less than 2 seconds, and 76.6% between 1 and 3 seconds for gesture performance. The duration and number of gestures with that duration for the full sample is shown in Figure 5. Horizontal axis displays the number of seconds a gesture took to perform/prepare for. Vertical axis displays the cumulative number of times that specific gesture duration appeared in the sample. Squares are denoting gesture performance, circles are denoting gesture preparation. It is noticeable that majority of both gesture preparation and performance durations are below 6 seconds.

While looking at just the gesture preparation duration, it would seem like participants may have responded intuitively rather than applying analogies, being that 78.2% took less than 3 seconds, and that similar levels of gesture performance duration 76.6%, could support the proposition by dual process theory of the alignment between the thinking process employed and the representation type. Figure 6 shows all gesture durations all participants performed during the Part 2 of the study.

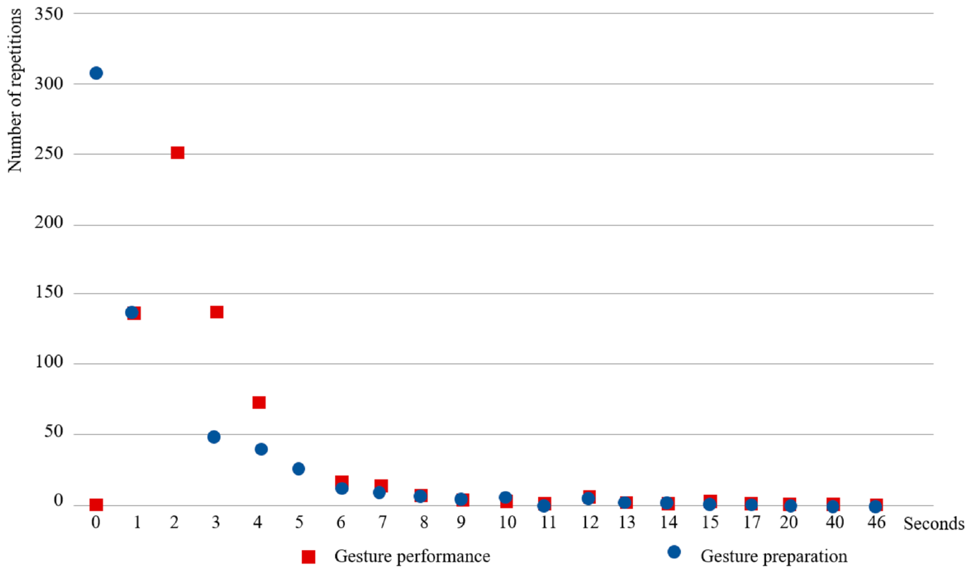

Figure 5. Most frequently occurred number of seconds for gesture preparation and performance (full sample).

Table 1. Most frequently occurred number of seconds for gesture preparation and performance (in %), for the range of 0–7 seconds (remainder of data excluded for space, but included in Figure 4).

Number of seconds	0	1	2	3	4	5	6	7
Preparation for the gesture (%)	44.1	19.8	14.2	6.8	5.6	3.4	1.9	1.1
Performance of the gesture (%)	0.1	20.1	36.4	20.1	10.2	6.2	2.3	1.9

Participant numbers are noted above each section showing durations of gesture preparation and performance in a sequence it was performed in by each participant. Vertical lines separate the participants. Number of seconds is noted on the vertical axis on the left. Columns above the horizontal line are visualising the duration of each gesture. Corresponding columns below are visualising the time it took each participant to think of each of those gestures, the time between the previous gesture and the performed gesture. Figure 6 further illustrates that majority of gestures took 1–3 seconds to perform, and that while for some gestures preparation time was longer, 44% of gestures were performed with no preparation (time spent thinking before the gesture performance). In Stage 1 of Part 2 of the study, there were breaks between each step of object development, and gestures performed following these are marked with a black border for both gesture preparation and performance, in Figure 6. These artificial breaks did not seem to influence gesture duration or preparation, as same durations also appeared where there were no breaks.

Table 2 shows the distribution of average performance time for the group of participants that performed Part 2 of the study first, and the group of participants that performed Part 1 first. It would be expected that there would be a statistically significant change in gesture performance times for the group that performed Part 1 first, if performing the Part 1 first leads to the participants learning to perform gestures faster. Testing this hypothesis using a

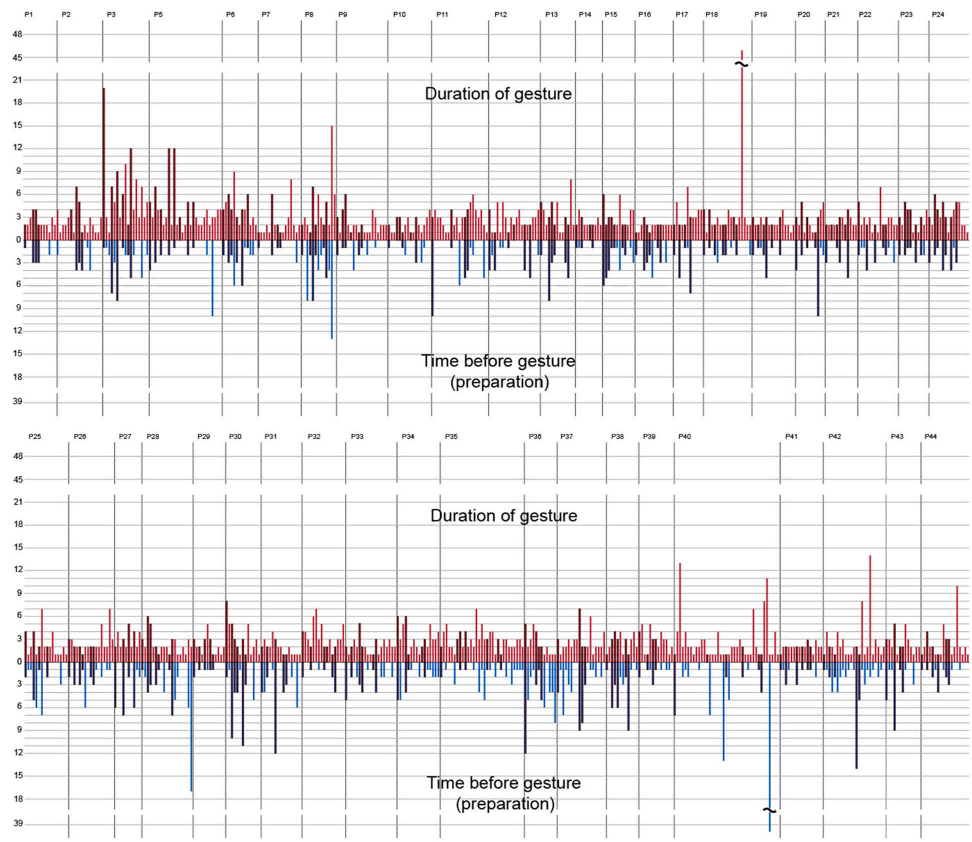

Figure 6. Gesture preparation and performance per participant per gesture.

Table 2. Difference in gesture preparation and gesture performance average duration times for participants that performed Part 2 first, and those that performed Part 1 first.

Part of the study performed first	Average gesture preparation time (s)	Average gesture performance time (s)
Part 2	1.79	2.95
Part 1	1.76	2.87

Chi-square independence test, a *p*-value of 0.0022 is derived, indicating the null hypothesis can be rejected and there is no evidence of change due to the study parts order change.

Outliers for longer preparation time

Longer gesture preparation and duration times have likely been influenced by individual participant abilities to describe their activities or complexity of gesture explanation during narration due to the complexity of the process that would have been followed in a CAD system for the creation of a particular shape. Figure 7 illustrates which activities, in some cases, required gesture preparation (top table) or gesture performance (bottom table) time longer than 7 seconds. Letters indicate which shape the activity was used for P – Phone, C(C2) – Cup (Cup 2) and H (H2) –- Hexagonal plate (Hexagonal plate 2). Hexagonal plate creation seemed to pose a challenge to some participants and some of the longest performances appear during that object creation. To create that shape using solid modelling in CAD, designers would typically create several planes at certain angles to ensure the sides of the plate were well defined. This approach not only requires reflection and analogy creation but also requires participants to shift between thinking about spatial characteristics of the object, and thinking about the actions they can perform to create certain elements of the object in a different representation (2D instead of 3D in some cases). Participant 40 has taken the CAD inspired approach and this is reflected in the duration of both gesture preparation and performance. For example, they take 40 seconds to think about activities they want to undertake, and the resulting process follows the approach often used in CAD systems, clearly forming the analogy with a known concept. Participant 28 took 17 seconds thinking about how they would create the sloping edges of the hexagonal plate. The actual gestures performed to create the shape were all under 3 s. Majority of other participants have interacted with this object as if they were creating it out of sheet metal, using their hands. They would cut out a hexagon out of an imagined sheet of material or create a flat hexagonal shape, and then bend the edges. Some would create a triangle, bend the edges and then rotate the triangle around its axis to form a hexagonal plate with bent edges. These participants typically performed their gestures in under 3 seconds each (e.g. participants 6, 7, 20, 23). However, some took longer to think of the activity they wanted to perform, as it was so different to what they would typically do using currently available digital tools (e.g. participants 8, 11, 28, 31). Their gesture preparation time, however, was 10 and 17 seconds, much shorter time than 40 seconds participant 40 required for the same activity, and this combined with the type of activity they proposed likely indicates that ultimately, they did diverge from analogy forming when creating a hexagonal plate.

Longer gesture preparation time more frequently happened when participants needed to decide how to undo an action, across all of the shapes, but only for four participants.

Outliers for longer performance time

Looking at gesture performance timing, there are a number of participants that did take longer than 7 seconds to perform certain gestures. For hexagon creation, Participant 18 took 46 seconds to explain how they would select an edge of the hexagon, Participant 3 took 20 seconds to explain how they would draw a circle, and Participant 8 took 15 seconds to describe pattern activity used to rotate a triangle into a hexagon around a central axis. Participant 3 took between 10 and 12 seconds to create a cup, cup handle and a box that would eventually be transformed into a phone casing. Participant 5 took 12 seconds to perform thicken the edge and zoom activities when creating a phone casing. Participant 40 took 11 and 14 seconds respectively to create a hexagon and shell a phone case. However, in vast majority of cases, the longer performance time seemed to be due to participants trying to accurately narrate and show their gestures, rather than difficulty with performing them. Overall, there was little similarity between the activities performed between different participants when gesture performance took longer than 10 seconds, so it is likely that personal skills and perception abilities of the participants might have been influencing their performance.

Participant	Preparation time in seconds																			
	7		8		9		10		11		12		13		14		17		40	
P3	Hollow the cylinder	C	Fillet the top	C																
P5							Create a handle	C												
P8			Create the cylinder	C																
P8			Fillet the edge	C									Pattern it around an axis	H						
P11							Create a plate slice	H												
P13			Hollow the cylinder	C																
P17	Create an extruded rectangle	P																		
P20							Create the cylinder	C2												
P25	Undo	H																		
P27	Pattern it around an axis	H																		
P28	Create a hexagon	H															Create a hexagon	H		
P30							Create a hollow cylinder	C2	Undo	C2										
P31											Manipulate	H2								
P36			Create the handle	C							Create a triangle	H								
P37	Create a triangle	H	Undo	H	Pattern it around an axis	H														
P38					Create an extruded rectangle	P														
P40	Create an extruded rectangle	P											Make a shell out of it	P						
P40	Make a shell out of it	P																	Create a hexagon	H
P42															Undo	C				
P43					Pattern it around an axis	H														

Participant	Performance time in seconds																					
	7		8		9		10		11		12		13		14		15		20		46	
P2	Pattern it around an axis	H					Create a handle	C														
P3	Hollow the cylinder	C	Hollow the box	P							Create a box	P							Create the cylinder	C		
P3	Fillet	P			Fillet the top	C																
P5	Round the edges	P									Thicken the top edge	P										
P5											Zoom in	P										
P6					Thicken the top edge	P																
P7			Fillet the edge	C																		
P8	Fillet the edge	C															Pattern it around an axis	H				
P13			Cut out triangles	H																		
P17	Undo	H																				
P18																					Select the edge	H
P22	Add the box	H2																				
P25	Undo	H																				
P26	Punch in the mic hole	P																				
P30			Create a cylinder	C2																		
P32	Create a hexagon	H2																				
P35	Fillet	C																				
P37	Pattern it around an axis	H																				
P40	Punch in the mic hole	P	Create a hexagon	H					Create a hexago n	H			Create an extruded rectangl e	P								
P42			Fillet	P											Make a shell out of it	P						
P44							Create a hexagon	H2														

Figure 7. Gesture preparation and performance per participant per gesture for activities with duration above 7 seconds.

For activities >7s — NUMBER OF ACTIVITIES THAT LASTED LONGER THAN 7 SECONDS; Activities performed — TOTAL NUMBER OF ACTIVITIES PERFORMED FOR EACH SHAPE

Object	Add bottom	Add the box	Bend sides	Bend the edge	Connect them (loft)	Create a bottom rectangle	Create a box	**Create a cylinder**	**Create a handle**	**Create a hexagon**	**Create a hollow cylinder**	Create a plane
Activity preparation								3	2	3	1	
Activity performance		1					1	2		4		
Cup	1							6	54		3	
Cup 2	2							16			18	
Hexagon			2	1	1					34		1
Hexagon 2		26								36		
Phone	1					1	2					
All shapes (total)	4	26	2	1	1	1	2	22	54	70	21	1

Object	**Create a plate slice**	Create a sheet	**Create a triangle**	**Create an extruded rectangle**	Create shape walls	Create the cylinder	Create the spherical handle	Cut out triangles	Cut the slot	Extrude the edges up	Extrude up	Fillet
Activity preparation	1		2	3								
Activity performance				1				1				3
Cup						42						11
Cup 2						5	23					9
Hexagon	24	1	25					2		1	2	
Hexagon 2			8									
Phone				33	1				1		1	22
All shapes (total)	24	1	33	33	1	47	23	2	1	1	3	42

Object	**Fillet the edge**	**Fillet the top**	Hollow the box	**Hollow the cylinder**	Join them	**Make a shell out of it**	Make edge thicker	**Manipulate**	**Pattern it around an axis**	Punch in the mic hole	Rotate
Activity preparation	1	1		2		2		1	4		
Activity performance	2	1	1	1		1			3	2	
Cup	10	2		31				13			
Cup 2				5							
Hexagon									23		1
Hexagon 2					1			8	5		
Phone			2			37	13	17		35	2
All shapes (total)	10	2	2	36	1	37	13	38	28	35	3

Object	Round the edges	Select	Select the edge	Slice triangles	Stick them together	Thicken the top edge	**Undo**	Undo handle	Undo Punch	Undo the pattern	Zoom in
Activity preparation							4				
Activity performance	1		1			2	2				1
Cup							11	1			2
Cup 2		1					9				
Hexagon			1	1	1		14			2	1
Hexagon 2		2					5				
Phone	5					3	9		3		4
All shapes (total)	5	3	1	1	1	3	48	1	3	2	7

Figure 8. All 702 gestures performed during the Part 2 of the study, compared to number of gestures that took longer than 7 seconds to prepare for/perform, classified per activity per object.

It is also noticeable that these longer gesture preparations and performances tended to appear towards the beginning of each object creation, and once the participants had chosen the approach they will take to object creation, thinking of gestures themselves was typically in under 4 seconds per gesture, and performing them was typically under 6 seconds per gesture, perhaps indicating that once the strategy has been devised participants focus on gesture performance for shape creation.

Figure 8 illustrates the range of activities used in object creation compared to the small percentage of gestures that took longer than 7 seconds. Activity categories where preparation took longer than 7 seconds for some participants are shown in bold font, and those where performance took longer than 7 seconds for some participants are represented by shaded cells. The number of gestures per activity that was longer than 7 seconds was shown in the two top rows. Rows below the list of the activities performed show a cumulative count of activities performed per object. 702 gestures were used to perform 49 different activities, and across those 14 activities incurred preparation time longer than 7 seconds (columns shown in bold font), and 20 activities incurred performance time longer than 7 seconds (columns shaded in light blue). However, compared to the full sample preparation activities that took longer than 7 seconds occurred, on average, for 4% of the gestures, and activities where gesture performance took longer than 7 seconds occurred, on average, for 3% of the gestures. That is to say that for frequently performed activities, only a small percentage of gestures took more than 7 seconds. The exceptions to this were cases where the activities proposed were only proposed by a handful of participants, like 'hollow the box' and 'create a box' (Participant 3), 'cut out triangles' (Participant 13), 'select the edge' (Participant 18) and 'thicken top edge' (Participant 5) aligning with the finding that the time was spent on accurately describing an unusual way of performing the activity, rather than physical challenges with its performance.

To put this in an easily quantified perspective, the number of gestures each of the participants took longer than 7 seconds to prepare for or perform was between 1 and 4 gestures out of on average of 40 gestures performed by each participant.

Comparison of performed gestures

Part 1 of the study focused primarily on manipulative tasks, with a minority of tasks dealing with shape modification. Part 2 focused primarily on shape creation and modification, with

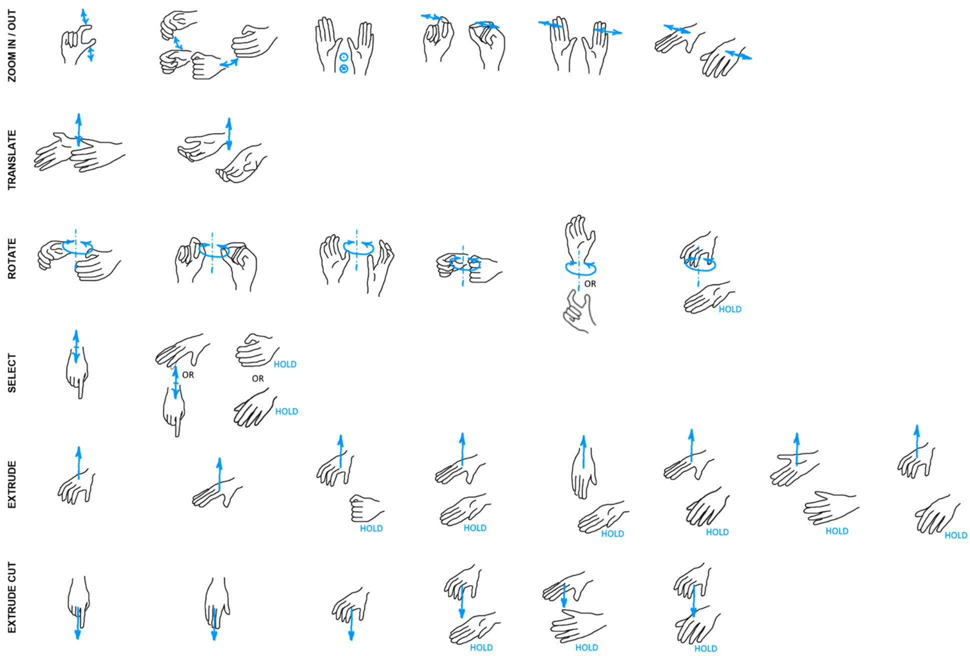

Figure 9. Examples of matching gestures across Part 1 and Part 2 of the study for the same activities.

minority of tasks dealing with manipulation. Therefore, it was not expected all proposed gestures would overlap, however, comparing the overlapping tasks it is noticeable that gestures performed were in many cases the same.

Same gestures that were suggested in both parts of the study were those used to zoom, translate, extrude, cut parts of the objects out and select parts of them. Some examples of these are shown in Figure 9. To zoom in or out objects were pushed or pulled, hands emulated the pinching gestures while moving away from each other or emulated gesture used to zoom in or out on a tablet/phone. To zoom in or out, sometimes open palms were pulled away from or moved towards each other in a specific plane. Zoom in/out by pinching or sliding hands across an imaginary surface was the only gesture where legacy, creating of analogies with use of phone or tablet, was noticed. They were, however, largely performed in under 3 seconds, likely indicating either the familiarity of the participants with the gesture or that they interacted with the screen they were seeing shapes on rather than the 3D shape they were viewing on it. To translate open palms were grasping or 'holding' the imagined object and pushing it in a direction of movement. Rotations were one- or two-handed grasps, either using the full hand or just two or three fingers of each hand, rotating the object in a desired direction. To select, objects were tapped with one hand or grasped with one hand to keep it in place and then tapped with the other hand. To extrude an object or cut out a shape from it, either one hand in a grasping or pointing form was motioned in the direction of the extrusion, or the same motion was performed with one hand while the rest of the part was held in place using the second hand.

Where gestures were not the same, they were of the same nature. For example, the use of gestures interacting with a 3D shape in a 3D environment resembling shaping clay was common, creating a cut in a material by digging out a hole or cutting it out by pushing it in using the pointer finger. While the combination of hand forms used differed based on the activity that only appeared in Part 1 or Part 2, most gesture elements used in these combinations for activities were the same. Gestures were also formed in relation to the shape of the 3D object and it was noticeable that hands were moving as if they were interacting with it as the participants were visualising it. Proposed gestures thus do match the representation mode, as the participants in majority of cases interact with 3D forms, shaping them in the air as if they were suspended in front of them, therefore we can interpret that they are likely performing an instinctive reaction rather than basing the gestures on a known analogy. The exception to this was the zoom in/out gestures, but it is highly likely that this was an effect of a legacy bias as participants were all exceptionally familiar with use of phones and tablets.

The repetition of gestures between the two parts of the study indicates that time limitation did not significantly impact the gesture propositions and hence did not negatively affect the gesture elicitation process by changing the nature of the gestures performed. As the activities performed were used to create a form in 3D space and then modify or manipulate it, in theory quick reactions were likely to be intuitive and matched the thinking processes required for the type and pace of interaction.

Limitations of the study

The study reported in this paper has several limitations. Following the study, participants were not asked about their perception of time in relation to gestures or their thinking processes. This choice was made consciously as the study duration and various activities participants engaged in meant that it was unlikely that they would accurately remember the entire process and be able to report on their thoughts, reasoning or influence match or mismatch between representation modes and interaction modes had on them. The findings were inferred from the patterns identified in the data collected. While measures were taken to maintain this process as objective and unbiased as possible, the difficulty in ascertaining the cognitive processes in participant minds would nonetheless introduce some uncertainty about the validity of findings. Without the use of technology allowing recording of brain activity it is impossible to claim with any degree of certainty that specific cognitive processes did indeed take place at specific stages of this study. Hence majority of the findings and conclusions were interpretations of the data collated during the study.

Due to the requirements of a larger study that the running of this study was compounded with, two parts of study did not require performance of same activities, meaning that only a certain common percentage of the same gestures would be performed. In ideal circumstances variables would be more controlled, and both parts of the study would focus on the same activities. This does not affect the core findings, however, it does reduce the sample size when nature of gestures was explored, especially if the same gestures were compared rather than their nature in general.

Recommendations for future studies

Introducing a time limitation did not have negative effects on the gesture elicitation, e.g. the nature of gestures did not change and majority of participants appeared to function in a space where thinking processes employed and representation types matched. Up to

95% of gestures during preparation and performance phases of activity completion took less than 6 seconds, 78.2% of gesture preparations took less than 2 seconds and 76.6% of gesture performances took less than 3 seconds. This means that less than 15% of gestures would be at risk of not being recorded or changed significantly due to time limitation if a 3-second limitation was to be imposed and less than 5% if a 6-second limit was to be imposed. It may also mean that short time required for gesture performance implies that gestures elicited were intuitive rather than thought through and based on creating analogies with previous experiences.

Therefore, if the goal of a gesture elicitation study is to identify intuitive gestures fit for matching representation and interaction modalities focusing on in-air 3D gestures, the recommendations would be to:

- limit gesture preparation and performance to a range of 3–6 seconds,
- include Q&A sessions after each significant section of the study to record any challenges participants had with the process.

Considering the study limitations, future work should focus on the exploration of the use of an AR environment with a Wizard of OZ setup that enables more certainty in the assessment that representation types and thinking processes are matched up. Additionally, the exploration of technologies allowing for more reliable recording of cognitive processes rather than relying on self-reported user perceptions of activities should be explored to improve the methodology of the elicitation process. Approaches towards the development of evidence-based methods for recording dual process models of cognition using neuroimaging have been proposed (Sowden, Pringle, and Gabora 2019), but not yet implemented. It was concluded in the field of psychology that reasoning and decision making are more complex than expected and that description of dual-process theory, while still plausible, may be more difficult to accurately categorise and describe than previously anticipated (Barrouillet 2011). That may also mean that development of a methodological approach for objective recording of a type of thinking involved in Type 1 or Type 2 thinking may still be ways away.

Conclusion

Observing the time taken to perform the gestures, there are no significant differences between Part 1 of the study where time was limited to 3 seconds and Part 2 of the study where there were no limitations. In Part 2, gestures were still performed in 2.86 seconds, on average, with 1.63 seconds taken for preparation. There was some variety between gesture durations proposed by different participants, however the longest ones were the consequence of a participant trying to accurately narrate their activities, rather than struggling to perform them using their hands. The more complex activities resulted in longer gesture preparation periods, typically towards the beginning of the period objects were created in, presumably while the creation strategy was still being established.

The recommendation would be that for design activities where Type 1 thinking is required, and intuitive response was preferred, sufficient time for gesture elicitation for a single activity is up to 6 seconds for gesture preparation and up to 6 seconds for gesture performance. While majority of gestures were thought of and prepared even quicker, 6 seconds is a slightly longer period chosen to account for any delays in gesture performance and provision of a safety buffer. This time frame appears to encourage quick and intuitive responses, reducing the chance the participants will create analogies with prior knowledge and experience that requires deliberate analysis. At the same time, the time limitation does not seem to negatively impact the performance and allows the completion of the activities and elicitation of gestures that match the nature of object representation.

Further research is required in methodological approaches for the improvement of representation types matched with thinking processes employed in creation and manipulation of 3D shapes, and more objective recording of cognitive processes.

Acknowledgements

For the purpose of open access, the author(s) has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availablity statement

The data that support the findings of this study are openly available in 10.15129/d3378868-1f7a-4381-ba5a-d868c510aa42.

ORCID

Tijana Vuletic http://orcid.org/0000-0002-9808-9087
Laura Hay http://orcid.org/0000-0002-3259-9463

References

Alcaide-Marzal, Jorge, José Antonio Diego-Más, Sabina Asensio-Cuesta, and Betina Piqueras-Fiszman. 2013. “An Exploratory Study on the use of Digital Sculpting in Conceptual Product Design.” *Design Studies* 34 (2): 264–284. https://doi.org/10.1016/j.destud.2012.09.001.

Alvarez-Santos, Víctor, Roberto Iglesias, Xose Manuel Pardo, Carlos V Regueiro, and Adrián Canedo-Rodriguez. 2014. “Gesture-based Interaction with Voice Feedback for a Tour-Guide Robot.” *Journal of Visual Communication and Image Representation* 25 (2): 499–509. https://doi.org/10.1016/j.jvcir.2013.03.017.

Amma, Christoph, Marcus Georgi, and Tanja Schultz. 2014. “Airwriting: A Wearable Handwriting Recognition System.” *Personal and Ubiquitous Computing* 18: 191–203. https://doi.org/10.1007/s00779-013-0637-3.

Arroyave-Tobón, Santiago, Gilberto Osorio-Gómez, and Juan F Cardona-McCormick. 2015. “AIR-MODELLING: A Tool for Gesture-Based Solid Modelling in Context During Early Design Stages in AR Environments.” *Computers in Industry* 66: 73–81. https://doi.org/10.1016/j.compind.2014.10.007.

Barrouillet, Pierre. 2011. “Dual-process Theories and Cognitive Development: Advances and Challenges.” *Developmental Review* 31 (2–3): 79–85. https://doi.org/10.1016/j.dr.2011.07.002.

Baudel, Thomas, and Michel Beaudouin-Lafon. 1993. “Charade: Remote Control of Objects Using Free-Hand Gestures.” *Communications of the ACM* 36 (7): 28–35. https://doi.org/10.1145/159544.159562.

Bhuiyan, Moniruzzaman, and Rich Picking. 2011. “A Gesture Controlled User Interface for Inclusive Design and Evaluative Study of its Usability.” *Journal of Software Engineering and Applications* 04 (09): 513–521. https://doi.org/10.4236/jsea.2011.49059.

Bolt, Richard A. 1980. ““Put-That-There” Voice and Gesture at the Graphics Interface.” Proceedings of the 7th Annual Conference on Computer Graphics and Interactive Techniques.

Buchmann, Volkert, Stephen Violich, Mark Billinghurst, and Andy Cockburn. 2004. "FingARtips: Gesture Based Direct Manipulation in Augmented Reality." Proceedings of the 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia.
Cash, Philip J. 2018. "Developing Theory-Driven Design Research." *Design Studies* 56: 84–119. https://doi.org/10.1016/j.destud.2018.03.002.
Cash, Philip, Jaap Daalhuizen, Dagny Valgeirsdottir, and Robin Van Oorschot. 2019. "A Theory-driven Design Research Agenda: Exploring Dual-process Theory." Proceedings of the Design Society: International Conference on Engineering Design.
Cash, Philip, and Anja Maier. 2021. "Understanding Representation: Contrasting Gesture and Sketching in Design Through Dual-Process Theory." *Design Studies* 73: 100992. https://doi.org/10.1016/j.destud.2021.100992.
Cha, Tong, and Sebastian Maier. 2012. "Eye Gaze Assisted Human–Computer Interaction in a Hand Gesture Controlled Multi-display Environment." Proceedings of the 4th Workshop on Eye Gaze in Intelligent Human Machine Interaction.
Chu, Chi-Cheng P, Tushar H Dani, and Rajit Gadh. 1997. "Multi-sensory User Interface for a Virtual-Reality-Based Computeraided Design System." *Computer-Aided Design* 29 (10): 709–725. https://doi.org/10.1016/S0010-4485(97)00021-3.
Cicirelli, Grazia, Carmela Attolico, Cataldo Guaragnella, and Tiziana D'Orazio. 2015. "A Kinect-Based Gesture Recognition Approach for a Natural Human Robot Interface." *International Journal of Advanced Robotic Systems* 12 (3): 22. https://doi.org/10.5772/59974.
Company, Pedro, Manuel Contero, Peter Varley, Nuria Aleixos, and Ferran Naya. 2009. "Computer-aided Sketching as a Tool to Promote Innovation in the New Product Development Process." *Computers in Industry* 60 (8): 592–603. https://doi.org/10.1016/j.compind.2009.05.018.
Dim, Nem Khan, Chaklam Silpasuwanchai, Sayan Sarcar, and Xiangshi Ren. 2016. "Designing Mid-air TV Gestures for Blind People Using User-and Choice-based Elicitation Approaches." Proceedings of the 2016 ACM Conference on Designing Interactive Systems.
Dong, Haiwei, Nadia Figueroa, and Abdulmotaleb El Saddik. 2015. "An Elicitation Study on Gesture Attitudes and Preferences towards an Interactive Hand-gesture Vocabulary." Proceedings of the 23rd ACM International Conference on Multimedia.
Esquivel, Rodríguez, Juan Carlos, Amilcar Meneses Viveros, and Nicolas Perry. 2014. "Gestures for Interaction between the Software CATIA and the Human via Microsoft Kinect." HCI International 2014-Posters' Extended Abstracts: International Conference, HCI International 2014, Heraklion, Crete, Greece, June 22–27, 2014. Proceedings, Part I 16.
Evans, Jonathan B. T., and Keith E Stanovich. 2013. "Dual-Process Theories of Higher Cognition: Advancing the Debate." *Perspectives on Psychological Science* 8 (3): 223–241. https://doi.org/10.1177/1745691612460685.
Fuge, Mark, Mehmet Ersin Yumer, Gunay Orbay, and Levent Burak Kara. 2012. "Conceptual Design and Modification of Freeform Surfaces Using Dual Shape Representations in Augmented Reality Environments." *Computer-Aided Design* 44 (10): 1020–1032. https://doi.org/10.1016/j.cad.2011.05.009.
Gonçalves, Milene, and Philip Cash. 2021. "The Life Cycle of Creative Ideas: Towards a Dual-Process Theory of Ideation." *Design Studies* 72: 100988. https://doi.org/10.1016/j.destud.2020.100988.
Guerra-Casanova, Javier, Carmen Sánchez-Ávila, Gonzalo Bailador, Alberto de, and Santos Sierra. 2012. "Authentication in Mobile Devices Through Hand Gesture Recognition." *International Journal of Information Security* 11: 65–83. https://doi.org/10.1007/s10207-012-0154-9.
Han, Y. C., and B. J. Han. 2014. "Virtual Pottery: A Virtual 3D Audiovisual Interface Using Natural Hand Motions." *Multimedia Tools and Applications* 73 (2): 917–933. https://doi.org/10.1007/s11042-013-1382-3.
Hernoux, Franck, and Olivier Christmann. 2015. "A Seamless Solution for 3D Real-Time Interaction: Design and Evaluation." *Virtual Reality* 19 (1): 1–20. https://doi.org/10.1007/s10055-014-0255-z.
Holz, Christian, and Andrew Wilson. 2011. "Data Miming: Inferring Spatial Object Descriptions from Human Gesture." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 811–820. New York, NY: Association for Computing Machinery. https://doi.org/10.1145/1978942.1979060.

Huang, Chih-Chieh Scottie. 2007. "Conceptual Modeling Environment (COMOEN)." Computer-Aided Architectural Design Futures (CAADFutures) 2007: Proceedings of the 12th International CAADFutures Conference.

Huang, Jinmiao, Prakhar Jaiswal, and Rahul Rai. 2019. "Gesture-Based System for Next Generation Natural and Intuitive Interfaces." *Ai Edam* 33 (1): 54–68.

Huang, Lu, Zongkui Zhou, and Rong Liu. 2014. "Research on Interaction-Oriented Gesture Recognition." *Sensors & Transducers* 163 (1): 316.

Hürst, Wolfgang, and Casper Van Wezel. 2013. "Gesture-Based Interaction via Finger Tracking for Mobile Augmented Reality." *Multimedia Tools and Applications* 62: 233–258. https://doi.org/10.1007/s11042-011-0983-y.

Jacob, Mithun George, and Juan Pablo Wachs. 2014. "Context-Based Hand Gesture Recognition for the Operating Room." *Pattern Recognition Letters* 36: 196–203. https://doi.org/10.1016/j.patrec.2013.05.024.

Jahani, Hessam, and Manolya Kavakli. 2018. "Exploring a User-Defined Gesture Vocabulary for Descriptive Mid-air Interactions." *Cognition, Technology & Work* 20: 11–22. https://doi.org/10.1007/s10111-017-0444-0.

Kela, Juha, Panu Korpipää, Jani Mäntyjärvi, Sanna Kallio, Giuseppe Savino, Luca Jozzo, and Sergio Di Marca. 2006. "Accelerometer-Based Gesture Control for a Design Environment." *Personal and Ubiquitous Computing* 10: 285–299. https://doi.org/10.1007/s00779-005-0033-8.

Khan, Sumbul, and Bige Tunçer. 2019. "Gesture and Speech Elicitation for 3D CAD Modeling in Conceptual Design." *Automation in Construction* 106: 102847. https://doi.org/10.1016/j.autcon.2019.102847.

Kim, Hyosun, Georgia Albuquerque, Sven Havemann, and Dieter W. Fellner. 2005. "Tangible 3D: Hand Gesture Interaction for Immersive 3D Modeling." *IPT/EGVE* 2005 (2005): 191–199.

Lee, Lik Hang, Tristan Braud, Kit Yung Lam, Yui Pan Yau, and Pan Hui. 2020. "From Seen to Unseen: Designing Keyboard-Less Interfaces for Text Entry on the Constrained Screen Real Estate of Augmented Reality Headsets." *Pervasive and Mobile Computing* 64: 101148. https://doi.org/10.1016/j.pmcj.2020.101148.

Liikkanen, Lassi A., and Matti Perttula. 2009. "Exploring Problem Decomposition in Conceptual Design Among Novice Designers." *Design Studies* 30 (1): 38–59. https://doi.org/10.1016/j.destud.2008.07.003.

Liu, Yanqiu, Xiuhui Wang, and Ke Yan. 2018. "Hand Gesture Recognition Based on Concentric Circular Scan Lines and Weighted K-Nearest Neighbor Algorithm." *Multimedia Tools and Applications* 77: 209–223. https://doi.org/10.1007/s11042-016-4265-6.

Liu, Jiaxin, Hongxin Zhang, and Chuankang Li. 2020. "COMTIS: Customizable Touchless Interaction System for Large Screen Visualization." *Virtual Reality & Intelligent Hardware* 2 (2): 162–174. https://doi.org/10.1016/j.vrih.2020.01.003.

Lopes, Daniel, Pedro Simões, Soraia Duarte de Figueiredo Parreira, Vitor Figueiredo Paulo, Paulo Amaral Nunes, Manuel Cassiano Rego, Pedro Silva Neves, and Joaquim Armando Jorge. Rodrigues. 2017. "On the Utility of 3D Hand Cursors to Explore Medical Volume Datasets with a Touchless Interface." *Journal of Biomedical Informatics* 72: 140–149. https://doi.org/10.1016/j.jbi.2017.07.009.

Matsumaru, Takafumi, and Ami Morikawa. 2020. "An Object Model and Interaction Method for a Simulated Experience of Pottery on a Potter's Wheel." *Sensors* 20 (11): 3091. https://doi.org/10.3390/s20113091.

Moore, Dylan, Jonathan Sauder, and Yan Jin. 2014. "A Dual-process Analysis of Design Idea Generation." International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

Morris, Meredith Ringel, Andreea Danielescu, Steven Drucker, Danyel Fisher, Bongshin Lee, M. C. Schraefel, and Jacob O Wobbrock. 2014. "Reducing Legacy Bias in Gesture Elicitation Studies." *interactions* 21 (3): 40–45. https://doi.org/10.1145/2591689.

Morris, Meredith Ringel, Jacob O Wobbrock, and Andrew D Wilson. 2010. "Understanding Users' Preferences for Surface Gestures." Proceedings of Graphics Interface, 2010, 261–268.

Nacenta, Miguel A., Yemliha Kamber, Yizhou Qiang, and Per Ola Kristensson. 2013. "Memorability of Pre-designed and User-defined Gesture Sets." In *Proceedings of the SIGCHI Conference on Human*

Factors in Computing Systems, 1099–1108. New York, NY: Association for Computing Machinery. https://doi.org/10.1145/2470654.2466142.
O'Connor, Timothy F, Matthew E Fach, Rachel Miller, Samuel E Root, Patrick P Mercier, and Darren J Lipomi. 2017. "The Language of Glove: Wireless Gesture Decoder with low-Power and Stretchable Hybrid Electronics." *PloS One* 12 (7): e0179766.
O'Hagan, R. G., Alexander Zelinsky, and Sebastien Rougeaux. 2002. "Visual Gesture Interfaces for Virtual Environments." *Interacting with Computers* 14 (3): 231–250. https://doi.org/10.1016/S0953-5438(01)00050-9.
Ojeda-Castelo, Juan Jesus, Jose Antonio Piedra-Fernandez, Luis Iribarne, and Cesar Bernal-Bravo. 2018. "KiNEEt: Application for Learning and Rehabilitation in Special Educational Needs." *Multimedia Tools and Applications* 77: 24013–24039. https://doi.org/10.1007/s11042-018-5678-1.
Piumsomboon, Thammathip, Adrian Clark, Mark Billinghurst, and Andy Cockburn. 2013. "User-defined Gestures for Augmented Reality." CHI'13 Extended Abstracts on Human Factors in Computing Systems, 955–960. https://doi.org/10.1145/2468356.2468527
Pons, Patricia, and Javier Jaen. 2020. "Interactive Spaces for Children: Gesture Elicitation for Controlling Ground Mini-Robots." *Journal of Ambient Intelligence and Humanized Computing* 11: 2467–2488. https://doi.org/10.1007/s12652-019-01290-6.
Pook, Polly K, and Dana H Ballard. 1996. "Deictic Human/Robot Interaction." *Robotics and Autonomous Systems* 18 (1–2): 259–269. https://doi.org/10.1016/0921-8890(95)00080-1.
Ramani, Karthik. 2015. "A Gesture-Free Geometric Approach for mid-air Expression of Design Intent in 3D Virtual Pottery." *Computer-Aided Design* 69: 11–24. https://doi.org/10.1016/j.cad.2015.06.006.
Robertson, B. F., and D. F. Radcliffe. 2009. "Impact of CAD Tools on Creative Problem Solving in Engineering Design." *Computer-aided Design* 41 (3): 136–146. https://doi.org/10.1016/j.cad.2008.06.007.
Robertson, Brett F, Joachim Walther, and David F Radcliffe. 2007. Creativity and the Use of CAD Tools: Lessons for Engineering Design Education from Industry".
Robinson, Graham, James M Ritchie, Philip N Day, and Richard G Dewar. 2007. "System Design and User Evaluation of Co-Star: An Immersive Stereoscopic System for Cable Harness Design." *Computer-Aided Design* 39 (4): 245–257. https://doi.org/10.1016/j.cad.2006.12.001.
Rodrigues, Élvio, Micael Carreira, and Daniel Gonçalves. 2014. "Developing a Multimodal Interface for the Elderly." *Procedia Computer Science* 27: 359–368. https://doi.org/10.1016/j.procs.2014.02.040.
Salman, Fazil, Yuanhui Cui, Zafar Imran, Fenghua Liu, Lijian Wang, and Weiping Wu. 2020. "A Wireless-Controlled 3D Printed Robotic Hand Motion System with Flex Force Sensors." *Sensors and Actuators A: Physical* 309: 112004. https://doi.org/10.1016/j.sna.2020.112004.
Santos, Beatriz Sousa, João Cardoso, Beatriz Quintino Ferreira, Carlos Ferreira, and Paulo Dias. 2016. "Developing 3d Freehand Gesture-based Interaction Methods for Virtual Walkthroughs: Using an Iterative Approach." Handbook of Research on Human-Computer Interfaces, Developments, and Applications, 52–72. IGI Global.
Schmidt, Albrecht. 2015. "Following or Leading? The HCI Community and New Interaction Technologies." *interactions* 22 (1): 74–77. https://doi.org/10.1145/2692980.
Shankar, S Sree, and Rahul Rai. 2014. "Human Factors Study on the Usage of BCI Headset for 3D CAD Modeling." *Computer-Aided Design* 54: 51–55. https://doi.org/10.1016/j.cad.2014.01.006.
Shesh, Amit, and Baoquan Chen. 2004. *Smartpaper: An Interactive and User Friendly Sketching System.* Computer Graphics Forum.
Sowden, Paul T, Andrew Pringle, and Liane Gabora. 2019. "The Shifting Sands of Creative Thinking: Connections to Dual-process Theory." Insight and Creativity in Problem Solving, 40–60. Routledge.
Trigueiros, Paulo, Fernando Ribeiro, and Luis Paulo Reis. 2015. "Generic System for Human-Computer Gesture Interaction: Applications on Sign Language Recognition and Robotic Soccer Refereeing." *Journal of Intelligent & Robotic Systems* 80: 573–594. https://doi.org/10.1007/s10846-015-0192-4.
Tsandilas, Theophanis. 2018. "Fallacies of Agreement: A Critical Review of Consensus Assessment Methods for Gesture Elicitation." *ACM Transactions on Computer-Human Interaction (TOCHI)* 25 (3): 1–49. https://doi.org/10.1145/3182168.
Tsandilas, T., and P. Dragicevic. 2022, April. "Gesture Elicitation as a Computational Optimization Problem." Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, 1–13.

Vatavu, Radu-Daniel, and Jacob O Wobbrock. 2015. "Formalizing Agreement Analysis for Elicitation Studies: New measures, Significance Test, and Toolkit." Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.

Vatavu, Radu-Daniel, and Jacob O. Wobbrock. 2016. "Between-subjects Elicitation Studies: Formalization and Tool Support." Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems.

Vatavu, R. D., and J. O. Wobbrock. 2022. "Clarifying Agreement Calculations and Analysis for end-User Elicitation Studies." *ACM Transactions on Computer-Human Interaction* 29 (1): 1–70.

Vidal, Rosario, and Elena Mulet. 2006. "Thinking about Computer Systems to Support Design Synthesis." *Communications of the ACM* 49 (4): 100–104. https://doi.org/10.1145/3476101.

Villarreal-Narvaez, Santiago, Jean Vanderdonckt, Radu-Daniel Vatavu, and Jacob O Wobbrock. 2020. "A Systematic Review of Gesture Elicitation Studies: What Can We Learn from 216 Studies?" Proceedings of the 2020 ACM Designing Interactive Systems Conference.

Vinayak, Sundar Murugappan, HaiRong Liu, and Karthik Ramani. 2013. "Shape-It-Up: Hand Gesture Based Creative Expression of 3D Shapes Using Intelligent Generalized Cylinders." *Computer-Aided Design* 45 (2): 277–287. https://doi.org/10.1016/j.cad.2012.10.011.

Vinayak, and Karthik Ramani. 2015. "A Gesture-free Geometric Approach for Mid-air Expression of Design Intent in 3D Virtual Pottery." *Computer-Aided Design* 69: 11–24. https://doi.org/10.1016/j.cad.2015.06.006.

Vuletic, Tijana, Alex Duffy, Laura Hay, Chris McTeague, Gerard Campbell, and Madeleine Grealy. 2019. "Systematic Literature Review of Hand Gestures Used in Human Computer Interaction Interfaces." *International Journal of Human-Computer Studies* 129: 74–94. https://doi.org/10.1016/j.ijhcs.2019.03.011.

Vuletic, Tijana, Alex Duffy, Chris McTeague, Laura Hay, Ross Brisco, Gerard Campbell, and Madeleine Grealy. 2021. "A Novel User-Based Gesture Vocabulary for Conceptual Design." *International Journal of Human-Computer Studies* 150: 102609. https://doi.org/10.1016/j.ijhcs.2021.102609.

Walker, Christopher R, Dula Nađ, Derek W Orbaugh Antillon, Igor Kvasić, Samuel Rosset, Nikola Mišković, and Iain A Anderson. 2023. "Diver-Robot Communication Glove Using Sensor-Based Gesture Recognition." *IEEE Journal of Oceanic Engineering* 48 (3): 778–788.

Wilson, Andrew, and Nuria Oliver. 2003. "GWindows: Robust Stereo Vision for Gesture-based Control of Windows." Proceedings of the 5th International Conference on Multimodal Interfaces.

Wobbrock, Jacob O., Htet Htet Aung, Brandon Rothrock, and Brad A. Myers. 2005. "Maximizing the Guessability of Symbolic Input." In *CHI'05 extended abstracts on Human Factors in Computing Systems*, 1869–1872. New York, NY: Association for Computing Machinery. https://doi.org/10.1145/1056808.1057043.

Wobbrock, Jacob O, Meredith Ringel Morris, and Andrew D Wilson. 2009. "User-Defined Gestures for Surface Computing." Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

Wu, Huiyue, Jianmin Wang, and Xiaolong Zhang. 2016. "User-Centered Gesture Development in TV Viewing Environment." *Multimedia Tools and Applications* 75: 733–760. https://doi.org/10.1007/s11042-014-2323-5.

Yamada, Moyuru, Jiang Shan, Katsushi Sakai, Yuichi Murase, and Keiju Okabayashi. 2014. "Immediately-Available Input Method Using One-Handed Motion in Arbitrary Postures." *Procedia Computer Science* 39: 51–58. https://doi.org/10.1016/j.procs.2014.11.009.

Yeo, Hui-Shyong, Byung-Gook Lee, and Hyotaek Lim. 2015. "Hand Tracking and Gesture Recognition System for Human-Computer Interaction Using low-Cost Hardware." *Multimedia Tools and Applications* 74: 2687–2715. https://doi.org/10.1007/s11042-013-1501-1.

Zengeler, Nico, Thomas Kopinski, and Uwe Handmann. 2018. "Hand Gesture Recognition in Automotive Human–Machine Interaction Using Depth Cameras." *Sensors* 19 (1): 59. https://doi.org/10.3390/s19010059.

Zimmerman, Thomas G, Jaron Lanier, Chuck Blanchard, Steve Bryson, and Young Harvill. 1986. "A Hand Gesture Interface Device." *ACM Sigchi Bulletin* 18 (4): 189–192. https://doi.org/10.1145/1165387.275628.