Posing and Acting as Input for Personalizing Furniture

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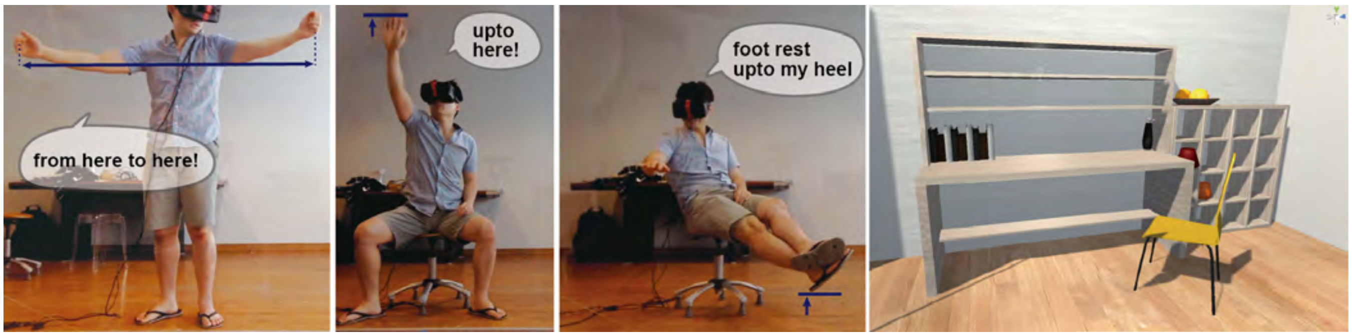

Figure 1. We explore a user-centered approach to personalizing objects. In our prototype, BodyMeter, users set the dimensions of furniture through full-body gestures and simple voice commands, while gaining a situated and first person view of the design using virtual reality.

ABSTRACT
Digital fabrication is becoming increasingly practical for customizing products to users' specifications. However, the design interfaces for customizing items have focused more on 3D modelling and less on how people use the object or how it fits around their body. In this paper, we explore a user-centered approach: using posing and acting as input for personalizing furniture. Users specify dimensions by referring to their body parts and using simple speech commands such as *"this wide"* or *"from here to here"*, while indicating a distance with their arms. A head-mounted display (HMD) provides instant feedback in real-size and allows users to experience and evaluate their virtual design as though it were a prototype. We report the formative and evaluative studies that indicate that the proposed approach engages casual users in the iterative design process of personalizing items in relation to their use, body, and environment.

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ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): Graphical user interfaces

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INTRODUCTION
Personal fabrication is an emerging topic in the field of human-computer interaction. Interest in this topic has been motivated by the trend in low-cost 3D printers and digital fabrication services that enable the fabrication of complicated shapes to the user's specifications. With digital fabrication, there is no penalty in creating unique objects [15], and it does not require training to the extent of traditional craftsmanship.

A key challenge in personal fabrication is to make the interface for designing 3D objects accessible for casual users. To date, most work in personal fabrication has focused on intuitive interfaces for creating 3D geometry. This is because the traditional computer-aided design (CAD) tools are created for professionals and are generally seen as too complicated for non-professionals. Therefore, research into novel interfaces using gestures, sketching [21], Augmented Reality [27], and existing objects [5] or people [31] as references or input, have demonstrated potential to support novices to create the objects that they want. However, ethnographic studies into re-appropriating everyday objects [26] and prototyping [2] suggest that there may be a need for additional support other than defining geometry: support that includes adapting, prototyping, testing, evaluating, and iterating.

The need for additional design support becomes apparent when we looked into how people select furniture. In physical stores, such as IKEA, we observed people using their arms to measure lengths, testing furniture for comfort, and acting scenarios of intended use. These are the gestures and actions that help us consider and understand the fit of the object with our needs. In this paper, we utilize these natural full-body gestures and actions to test and set the dimensions of custom furniture.

Our contributions are threefold: (1) two qualitative studies that uncover how users think with their body when specifying dimensions of their furniture; (2) a novel customization interface that uses full-body gestures and voice commands as input; and (3) an evaluative study that indicates that our approach engages users in an iterative and reflective design process and helps them focus on their needs.

RELATED WORK

Design interfaces that support furniture customization at home must enable people to express and understand their needs, as well as to engage them in a design workflow. We argue that this is as important as providing people with the ability to create and adapt geometries. Therefore, we build upon the experience prototyping technique [2]. Through active interaction with situated virtual prototypes, we aim to enable users to gain insights into how they use their furniture while they are specifying the dimensions.

In order to understand how users design, we were inspired by the early work of Hummels in gestural interfaces for conceptual industrial design. Hummels [10] allowed designers to freely gesture imaginary designs, and the design outcome was captured through Wizard of Oz, and hand-drawn by an experienced visualizer. In this way, she uncovered patterns and rules in the gestures that designers make in order to support their thinking and express their ideas. In contrast, we investigate mundane customization scenarios situated in the home, which we consider as "variant design" [19], and we evaluate our findings in a virtual reality (VR) prototype. In this related work section, we discuss the design interfaces for personal fabrication that make use of situated or embodied interaction and the related studies in non-professional design activities.

Situated and Embodied 3D Modelling Tools

A common approach to make 3D modelling tasks accessible to casual users is to provide a 2D sketching interface to create 3D geometry. For example, Sketchchair [21] allows users to design a chair with a few pen strokes and the software generates the 3D geometry ready for fabrication. However, similar to various online mass customization configurators, the spatial impact of a 3D design is difficult to imagine from a 2D screen. Therefore, some projects [14] explored situating the design in the users' intended context by enabling them draw on photos and reconstructing the object's 3D geometry.

Other related studies let users to draw directly in 3D in real-size to make the designs experiential. For example, hand-held tablets with spatial awareness to interact with the 3D physical world [4]. T(ether) [12] is one such tablet-based system that offers direct manipulation of virtual objects seen through a tablet. Several related projects allow users to sketch directly in free space [7]. Situated modeling [13] enables users to design furniture through stamping primitive shapes in the use-environment using augmented reality and hand-held tools. Typical feedback for these embodied design systems is that users appreciate the one-to-one scale and spatial understanding. We build on these efforts through enabling users to customize objects directly in 3D, but we focus on uncovering natural ways of interaction and on how users relate design decisions to their design needs.

A few pr ojects have made use of the body as input for design. For example, Mirror Mirror [20] allows users to design new clothes in front of the mirror by using on-body gestures. Dressup [29] asks users to design garments directly on a tracked physical mannequin with tracked cutting and surfacing tools. Body Avatar [31] is a first person 3D modeling system that creates avatars that are attached to the body in real scale. The virtual avatar moves and deforms according to the user's body posture. We build upon this work and consider body posture and body parts in order to relate the virtual design to the user experience. However, based on the results of our gesture elicitation study, we use full body gestures.

Designing Natural Gesture based Systems

Some studies into natural interfaces for interacting with 3D geometries [9, 27] have been based on user-defined gestures [30]. These gestures are derived directly from CAD operations, such as extrude, revolve, and scale objects. We build upon the Wobbrock's approach to synthesizing user-defined gestures but incorporate two significant differences: 1) we work on furniture, instead of a tabletop, and deal with full-body interactions, and 2) we derive gestures from user experience rather than from existing geometry operations.

Hoang et al. [8] proposed a modelling system using ultrasonic gloves that measure distance and orientation for users to specify cube dimensions. In order to customize more complex objects, we build on the work of Bolt [1] that enables users to move shapes using simple voice commands, such as *"Put that there"*, with a matching gesture. Mignot et al. [17] investigated the addition of natural speech to manipulate 2D layouts and found that most users employed synergic multimodality in commands, e.g. *"Put this armchair beside the other one"*. We extended these works with speech commands such as *"From here to there"* or *"Until here"* that allow users to refer to one's entire body or the environment.

Understanding Everyday Designers

Everyday design activities by non-professionals have been explored using ethnographic methods in contextual design [26]. Studies of crafts and hobbies, such as gardening and knitting, and DIY communities highlight the creativity and resourcefulness of individuals. The ability to iterate and adapt products is central to the practice of everyday design in families. Seemingly simple tasks such as choosing a color for a wall [28] are preceded by a design process that begins with a vague notion that considers the existing furniture and perceptual attributes regarding color tones. Several sources are used for inspiration and information such as magazines and display homes. Insights gained from these studies indicate a discrepancy between the design needs and design processes of people, and the current focus on creating geometry in customization tools. Therefore, in this paper, we begin with a formative study in participants' living spaces in order to understand how they think about their furniture and then attempt to develop a fitting design interface to support them to personalize new furniture.

FORMATIVE STUDY

In the formative study, we identify how users describe their ideal furniture and which design aspects they describe. As depicted in Figure 2, the study is situated at the participants' home, because we expect participants to be motivated by the everyday context, e.g. the desk that they use most often, and its surrounding items while talking about their needs.

Procedure

We conducted semi-structured interviews that lasted about one hour per participant. First, we sensitized the participants by asking them about their daily lives in relation to their desks. They were asked to rate the comfort levels for their desks and to describe their ideal desks (what their needs are, and how they would redesign it). We video recorded the sessions with two cameras, one overview camera to capture the user's gestures and movements, and another camera to capture detailed expressions. The results were analyzed using bottom-up affinity diagramming. The participants were compensated the equivalent of 10 Euros.

The participants (4 females, 4 males) were recruited from a local university, who are all living on campus, with an average age of 23.75 (SD = 1.38). Since their apartments are furnished, the participants use the standard desk issued by the university (Figure 4, left). We selected this group of participants because they are likely to be able to point out what they want changed in their desks, are heavy users of their desk (6.6 hours daily average), and all have similar desks and room layouts.

Results

Although the standard desks look similar, the participants used them in diverse ways depending on their lifestyle or the items they have. All participants had their own issues, some of which were resolved through appropriation [26]. For example, P1 was not tall enough to touch the ground with her feet with a chair height to fit her desk; therefore, she always put an empty bottle of water below the desk as the footrest. However, some issues were more difficult to resolve, such as being unable to reach highest bookshelf, which resulted in the desktop being messy. Because P2 has her laptop close to her when using it, the space behind the laptop remained unused and could be utilized better.

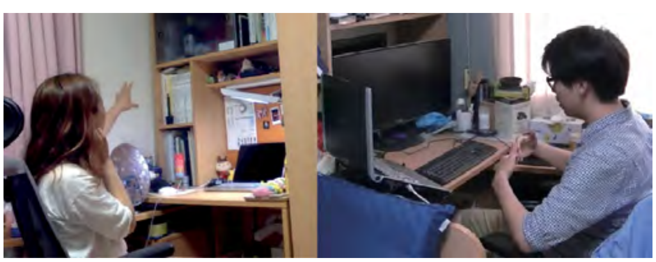


Figure 2. The formative study was situated in the participants' apartments. The rooms may have similar layouts and furniture, but we found a wide variety in how the desks were used and in their wishes and needs.

Figure 3. The gesture elicitation study was undertaken in a laboratory set up to match the participant's on-campus room. Participants used various gestures to specify the dimensions of their ideal desk.

We observed several participants acting out how they use their desk. For example, P6 performed typing gestures whilst sitting to demonstrate how he used his desk with a computer. All participants illustrated how they wanted to change their desks using their body and objects in their surroundings. P3 said, *"I want to set the desk height at such a position that I won't have to shrug my shoulders when typing on the keyboard"*, or as P8 stated, *"I want my desk deep enough to put papers in front of the keyboard."* Some participants also mentioned aesthetic factors, such as color and material, but functionality was their primary concern.

In addition to using their hands, participants frequently referred to other body parts, such as their feet or waist, because it was difficult to describe the large desk using only two hands. For example, P4 used his foot to describe the height of the footrest so that he did not need to bend over. Also, P7 stretched both arms out in order to illustrate the maximum width of the desk: *"I want to maximize the space on my desk without having to stand up to pick up things. Therefore, the length between my fingertips when I stretch my arms out should be the maximum width of the desk."*

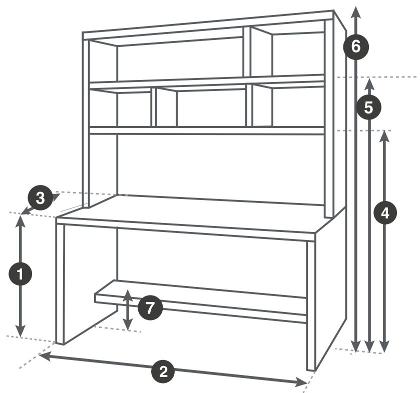
Discussion

The formative study revealed the rich and embodied way of how people describe their needs and which dimensions are important for them. The participants used full-body gestures, poses, and nearby objects as props, which is important for re-enacting their experiences with their desks and describing their ideal desk. The results warrant further examination into the potential of user-centered understanding in identifying personal customization needs and specifying dimensions.

GESTURE ELICITATION STUDY

In the second gesture elicitation study, we built on the findings of the formative study and we attempted to uncover how participants specify dimensions for a custom-made imaginary desk.

We recruited eighteen participants (9 males) between the ages of 21 and 30 years (M = 22.72, SD = 3.06), who use similar study desks provided by the university. Therefore, we could use the standard parameters as depicted in Figure 4. Half of the participants did not have prior experience with CAD software and 14 had experience purchasing furniture. The study took between 40 to 60 minutes for each participant, and we paid them the equivalent of 10 Euros.



	height of eye	height of shoulder	height of chest	height of waist	height of elbow	height of wrist	height of palm	height of fingertip	height of heel	height of sole	fingertip to shoulder	fingertip to waist	fingertip to elbow	fingertip to palm	fingertip to fingertip	palm to palm	palm to toetip	elbow to elbow	elbow to wrist	wall to palm	room ratio / fitting	chair height	
1 Desk height			1	2	9	1	5																18
2 Desk width															7		3	1		1	6		18
3 Desk depth											3	2		2		4	1			5	1		18
4 1st shelf height	2	1	1					14															18
5 2nd shelf height	4							3					3		3	4			1				18
7 Foot rest							4		9	2												3	18

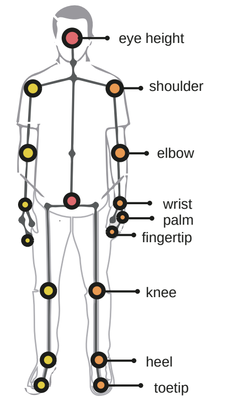


Figure 4. (left) The standard issue desk used by all participants and used throughout the paper. The desk has a footrest below and three shelves above the desktop. In the gesture elicitation study, the participants referred to several body parts and nearby objects. (center, right) The number of times each body part was referred to for each parameter are presented.

Task and Procedure

The study was done in a lab set up to match the participant's room layout, as depicted in Figure 3. We furnished the room with a chair, cabinet, lamp, and bookshelves, but not their desk. As such, the participants could freely imagine their ideal desk through gestures without physical restrictions of an existing desk.

The study began with a pre-interview priming session [18] that recalled their personal experiences regarding their desks. Once a participant was fully sensitized, we asked to specify the optimal dimensions and position by using gestures and a think aloud protocol. The seven parameters (Figure 4) that were described in the previous study were used .

We followed the method described by Wobbrock et al. [30]; however, instead of presenting a modification applied to the desk and then trying to elicit the appropriate gestures, we asked the participants to specify the parameters, and we captured the entire process leading up to the decision. This was because, in pilot study, we found that the participants used multiple gestures to understand how they use the desk and to estimate a dimension before they finalized it.

In the post-interviews, we discussed the rationale of the gestures they used to set a parameter. To support their memory, one of the researchers had drawn sketches of their gestures on the interview form. The entire study took about an hour on average. The videos were analyzed, and for each gesture the representative frame-grab, transcriptions, and related comments were printed onto paper cards. This made the video available as a resource [3] for interpretation and discussion by the researchers.

Results and Observations

It took the participants 3-5 minutes before they specified a dimension. They frequently accompanied their final decision with a single voice command such as *"from... to..."* , *"until..."*, or *"up to..."*. As depicted in Figure 4 *(center)*, they referred to several body parts and objects in the room to describe the dimensions. The height of the tabletop was usually set by referencing the height of a body part from the floor. In contrast, the depth and width were always specified between two body parts or from the wall to a body part. We observed two approaches when specifying the book shelves. Some of the participants specified the height based on reachability, whereas others did so by considering the distance between the shelves. Participants used gestures for various purposes, and we categorized them into three types: ruler gestures, embodied thinking gestures, and acting gestures.

Ruler Gestures: Using Body to Measure

With *ruler gestures*, the participants used their bodies as a type of ruler to capture or represent measurements. For example, P1 used the distance between his elbow and his fingertips (Figure 5, *R1*) to approximate the height of a shelf to fit his wine bottles. P10 used the distance between her fingertip and opposite shoulder to set the depth, as this was a personal unit to recall the dimensions (Figure 5, *R3*). In addition to using their body as a reference, some participants also used their body as a tool to copy existing objects. For example, P6 measured a sheet of a paper using his palms to set the depth of his desk.

Embodied Thinking Gestures: Using Body to Think

With *embodied thinking gestures*, the participants moved their body or arms to search for an optimal dimension. The participants usually estimated the dimensions with a slow and continuous motion, such as varying the distance between the palms of their hands (Figure 5, *E1, E2*) or between the wall and a specific body part (Figure 5, *E3*), while observing the result. This type of *epistemic action* [11] was frequently observed just prior to the participants specifying a dimension.

Acting Gestures: Using Body to Simulate

With the *acting gestures*, the participants simulated usage scenarios with their body. For example, P15 wanted to be able to stretch his legs when using his desk. Therefore, he specified the depth of the desk using the distance from his toes to his waist while seated and stretching his legs (Figure 5, *A4*). To determine the height of the desk, another participant used the position of her elbows while simulating a comfortable seated posture (Figure 5, *A1*).

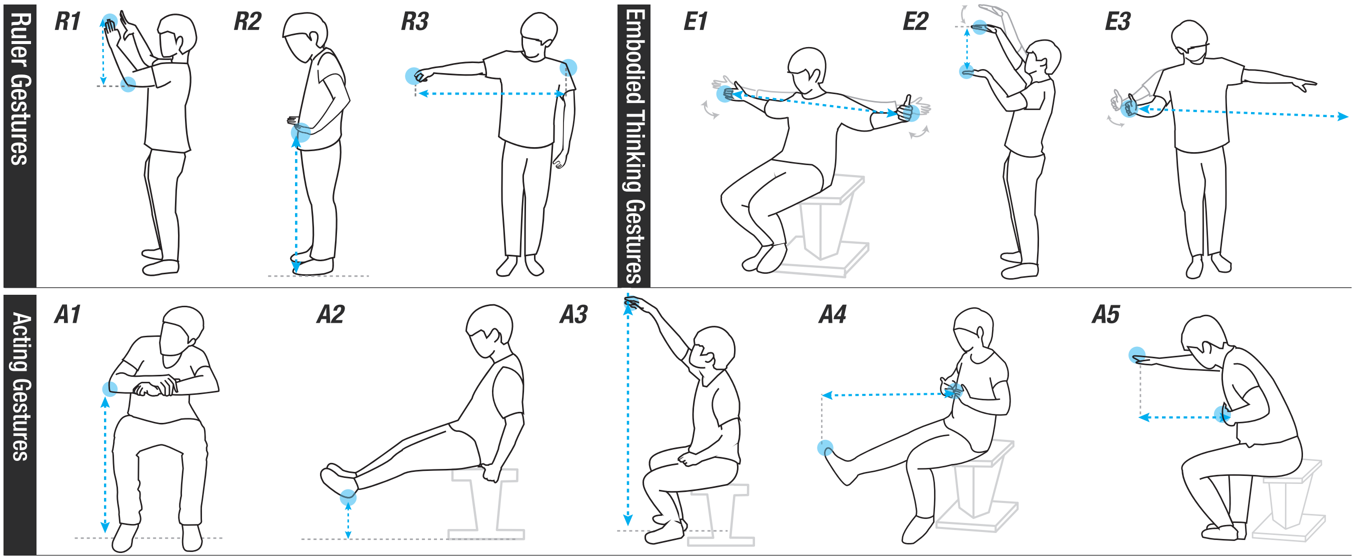


Figure 5. Selected examples of the gesture types: (R1) ***"The shelf distance is about the same length as between my fingertip and elbow"*****, (R2)** ***"The desk height reaches up to my waist"*****, (R3)** ***"This is about the common desk depth I used before"*****, (E1)** ***"The desk width is about this much (moving arms)"*****, (E2)** ***"My books are about this tall, so the shelf should be a bit higher... like this? (moving hand)"*****, (E3)** ***"The desk width might be from the wall to somewhere here (moving hand)"*****, (A1)** ***"The desk height is to my elbow, at this comfortable position"*****, (A2)** ***"The foot support until my heels"*****, (A3)** ***"The shelf is to here, so that I can reach it while sitting."*****, (A4)** ***"The desk depth is from the tip of my toe to my palm so that I can stretch my legs"*****, and (A5)** ***"The desk depth is from my fingertip to my waist so that I can touch the entire desk."***

Mixed Use of Gestures

The participants fluently mixed multiple gesture categories per dimension. For example, P18 used her palm and the walls to estimate the depth of her desk (*embodied thinking gestures*) as she stretched her legs like she does while studying (*acting gestures*). Furthermore, P7 used various gesture types consecutively. He ended up alternating between demonstrating the reachability of a shelf (*acting gestures*) while checking the required spacing using his stretched hand as a ruler (*ruler gestures*) to ensure the fit of his books.

Discussion

The voice commands suggest a dialog style of the user interface for an embodied customization task. The full-bodied gestures that were observed were similar to those seen in the formative study. However, the results of this study revealed three main patterns of making decisions for to set dimensions.

Pattern 1, informed by ergonomics: Using acting gestures, the participants set the dimensions directly using their body postures without considering other factors. This was frequently applied for the desk height, where one's personal ergonomic pose is the most important factor. These were also often applied to shelf heights to simulate reachability.

Pattern 2, informed by object fit: The participants specified dimensions that can accommodate the items they often use. Sometimes, they specified a dimension through objects, e.g. *"A desktop depth that fits my laptop and an A4 size book."* Usually, the participants wanted to add a bit more length to the desk, e.g. *"This wide plus about one span of my hand to have extra space."*

Pattern 3, informed by the context of the room: Some participants preferred their desk to be as large as possible. Thus, they referred to the structures within the room, such as the wall or other furniture, as anchor points in order to make their personal desk fit the space.

BODYMETER DESIGN

Although the gesture elicitation study revealed patterns, gestures, and poses that the participants used to specify their custom desk, it did not provide visual or tangible feedback on the parameters. In addition, as the gestures were elicited in a strict order, the study could not reveal the flow of a design process. To investigate this, we developed a prototype called BodyMeter, which uses a multimodal interface and virtual reality for situated visual feedback.

Design Interface

Based on the previous studies, we developed a synergic multimodal command language to specify the dimensions of a desk. Each voice command begins with the parameter to be modified, e.g. *"desk height"*, followed by a description of the dimension, *"up to my hand"*. The participants can illustrate the dimensions using three types of indicators.

Between two points: Set a distance using the indicator *"From...to..."* between two body parts or between a body part and the environment. For example, the user can set the desk width as an arm length by saying *"Desk width, from my right shoulder to my right fingertip"* while stretching the right arm. Then, the system automatically calculates the distance between the user's shoulder and fingertip, and sets that measurement as the width.

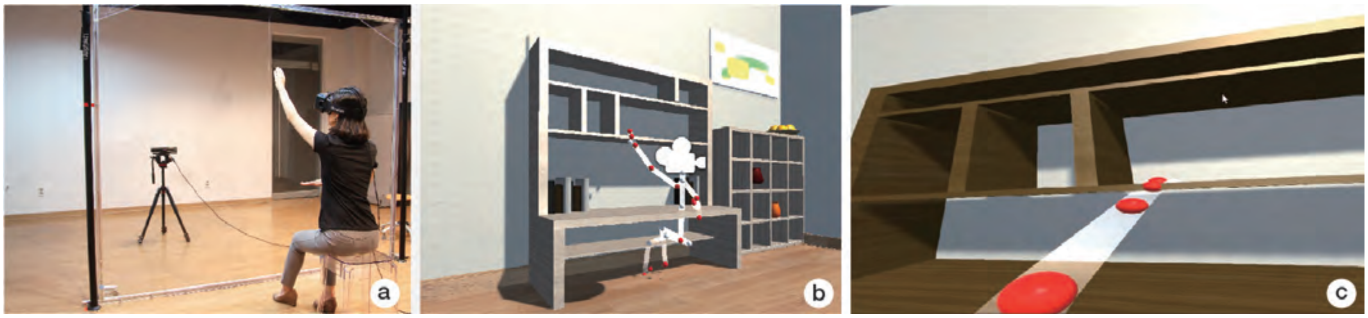


Figure 6. The BodyMeter prototype used in the evaluation study. (a) The user wears an HMD and a Kinect captures the user's pose, (b) the virtual environment from a third person view, and (c) from a first person view. The body parts that can be used for customized commands are marked with red dots.

To a point: A position can be set using the indicator *"Up to..."*, e.g. *"Shelf height, up to my shoulder."* In the gesture elicitation study, we only observed this indicator for setting heights, but it can also be applied for depth: *"Desk depth, up to this palm."* This function is particularly useful for people who set their dimensions using ergonomic poses or reach.

Adding extra length: The third indicator adds certain amounts of length to previous parameter through instructing *'Add..from..to..'*. This command originates from the decision-making patterns where the participants tended to add extra length or margin. The additional length is added to the side of the object that the user is standing at. As seen above, users can use two different types of referents. When they refer to a body part, the voice commands are augmented with gestures, holding the specified body part in the intended 3D position, similar to what was achieved in "Put-That-There" [1]. They can also refer to objects in their environment, such as the '*walls*' or '*nearby furniture*'.

BodyMeter Prototype

To engage the participants in designing a personal desk for their room, we prepared a furnished virtual room that had a similar layout to their dorm (Figure 3). We included the walls, windows, and furniture, such as bookshelves, as they were frequently referenced in the earlier studies. We decorated the space with relevant objects such as books, plants, and lamps.

In BodyMeter, users wear a HMD (Oculus Rift DK2) to gain a first person view of the virtual environment in a real-size scale. The prototype, which was built using Unity3D, visualizes both the furniture and a representation of the user's body. As seen in Figure 6b, the red circles drawn on the body indicate which parts can be used to specify dimensions. The geometry of the desk is parametric, driven by the parameters shown in Figure 4 and it can be updated in real-time with gestures and voice commands.

The physical experiment room was sufficiently large ($6m \times 7.2m$) for the participants to freely walk around while designing their desk. We captured the body poses and locations using skeleton tracking from Microsoft Kinect v2. The eye position that was captured by the Kinect was used to position the first person view for the Oculus; however, the sensors of the Oculus were used for the orientation because of their low latency. We provided a height adjustable chair and an acrylic wall ($2m \times 4.8m$) that was co-located with the wall in the virtual environment in order to provide tangible feedback, as depicted in Figure 6a. The wall was made from clear acrylic and is invisible to the Kinect in order to robustly capture the user's full pose near the wall or when seated.

Figure 7. Speech recognition was performed using a trained operator implementing the Wizard of Oz technique. Sample command operations are depicted on the bottom.

Speech Recognition

In order to capture the participants' spontaneous formulation of commands and address potential ambiguities, we resorted to a Wizard of Oz technique for voice commands, , similar to Mignot [17]. This allowed for variations in the naming of body parts and could also resolve abbreviated descriptions, such as *"here"*, when the meaning was clear from the participant's gestures.

As depicted in Figure 7, the operator sat near the participant and used a keyboard with clearly marked hotkeys for input commands. The hotkeys were composed of five modules: the parameters of the desk, body parts, environmental references (left wall, right wall, front wall), and *"add"* and *"undo"* buttons. The order of the keys was coded to match the order of the participants' commands: target parameters are pressed first, followed by the body parts. The operator was fluent and fast in entering the commands, and the dimensions were updated with small unperturbing lag.

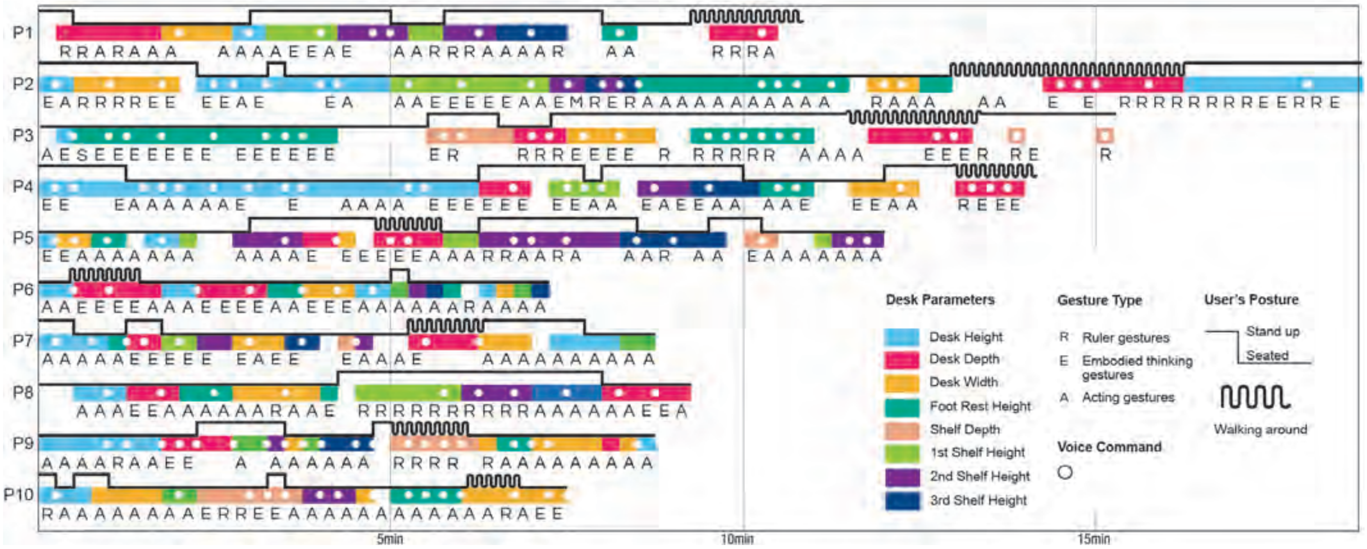


Figure 8. The flow of the evaluation study is visualized per participant. As seen in the figure, all participants alternated between seated and standing positions while some walked around. The participants went through the desk parameters, classified by color, and used several gesture types.

USER EVALUATION

In the third study, the participants customized their desks using the BodyMeter prototype. The purpose of this study was to verify the multimodal, body-centric approach observed in the previous studies in a customization workflow. We invited 10 participants (5 males) at random from the previous study. The two studies were four weeks apart, and these participants were already primed with understanding of their needs for their desks. The participants were between 19 and 30 years old (M = 22.70, SD = 3.50), and half of the participants did not have experience with CAD software. The study took about an hour per person, and we compensated them with the equivalent of 10 Euros.

Task and Procedure

We began with brief instructions about the study setup and BodyMeter interface, followed by a 10-minute tutorial. In the tutorial, the participants were asked to customize the height and the width of a door to fit their body, and we guided them where necessary. In the main study, the primary task consisted of personalizing a desk for their room. We captured their design activity from four different perspectives: two virtual cameras (the virtual environment from the perspective of the participant and a third person, showing the participant and the desk) and two real cameras (capturing the participant from the front and side). In the post-session interview, we showed the participants a picture of their personalized desk, discussed their process, and asked for comments and suggestions.

Results

Customization Process using BodyMeter

We observed that BodyMeter engaged participants in an iterative design process, whereas the participants specified the parameters consecutively in a predefined order in previous gesture elicitation study. After an initial setting, the participants often revisited the parameters to make refinements. As depicted in Figure 8, the participants fluently used various gestures and body parts as they adapted the desk to their needs. Whereas most participants adjusted the parameters in rapid succession, P2 and P3 used a slightly different process and spent more time per parameter.

The participants alternated between sitting on their chair, standing, and walking around. These movements allowed them to experience and evaluate their design decisions from various perspectives and to focus on specific aspects of their design. P1 optimized the height of the second shelf by repeatedly standing up and sitting down, while constantly making modifications to both the first and second shelves (Figure 8, P1 around 4-7 min). Using this change in perspective, different parts of the design was inspected and inspired changes. While sitting on the chair or standing in front of the desk, the participants were engaged in functionality and ergonomics. However, when they moved around and stepped back and observed the desk from a third person view, they focused on the fit of the desk in the environment. This frequently resulted in adjustments to the width of the desk. For example, P10 adjusted the width in order to make space between the desk and the bookshelf. (Figure 8, P10 around 6-7 min, *"I haven't thought about it before, but this space is necessary to put my suitcase"*).

Using the BodyMeter Interface

During the design session, all participants were fully engaged in the VR environment. They often touched the wall and did not have issues standing up or walking around to make gestures and poses. The height adjustable chair made users comfortable while designing their desk because they tried to set the chair to their preferred height prior to the design session. It was particularly useful to P10, because she prefers to sit high. She mentioned, *"Personalizing while sitting on the pre-*

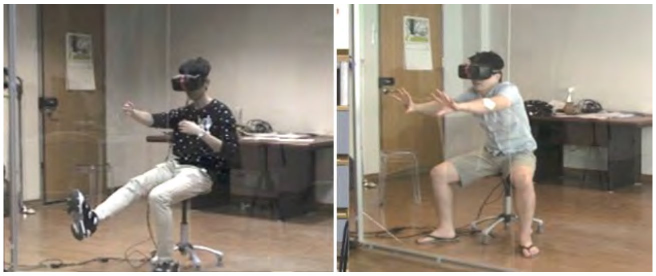


Figure 9. Participants used the acrylic wall to gain a sense of depth. (a)P8 put his foot on the wall and refer from the length of leg, (b) P9 touched the wall using hands and refer from the length of arm length.

ferred height of chair is very useful, particularly for setting the desktop height. I can apply my personal sitting habit."

The participants mentioned that using gestures and speech was intuitive and easy to process because they did not need to learn new UI elements. Throughout the process, the participants exhibited similar gestures to those we observed previously, which indicates that our prototype did not restrict their natural customization process. However, most participants had difficulties in sensing depth while wearing the HMD. They relied on the acrylic wall that was co-located with the position of the virtual wall. They could get a sense of depth through touching the wall with their foot or hand, then they used their body as a ruler to specify their ideal depth (Figure 9).

The participants mentioned that using gestures and speech was intuitive and easy to process because they did not need to learn new UI elements. Throughout the process, the participants exhibited similar gestures to those we observedused previously, which indicates that our prototype did not restrict their natural customization process. However, most participants had difficulties in sensing depth while wearing the HMD. They relied on the acrylic wall that was co-llocated with the position of the virtual wall. They could get a sense of depth through touching the wall with their foot or hand, then they used their body as a ruler to specify their ideal depth (Figure 9).

Design Results

Despite having only 7 parameters, all the participants succeeded in personalizing the desk according to their lifestyle and needs. When we presented a photo of their final design, 9 out of 10 were satisfied with their final output, e.g. P8: *"I am happy with this output as I can almost imagine how the product will look. I feel like I have already used it."*

The designs of P3 and P10 stood out as they went through different decision-making approach based on their lifestyles and needs. P10 (1.67m height) likes to sit on chairs that are high and attributed to her frequent studying as the cause for needing a desk that is comfortable to sit at (Figure 10a, left). These needs make 'ergonomic body postures' as primary input. By contrast, P3 (1.81m height) did not study at his desk often and wanted a large desk space for maximum storage potential (Figure 10a, right). So he often referred to environmental objects such as the walls and the floor (pattern 3). Several participants referred to objects in the virtual environment and used these objects as reference sources. P5, for instance, copied the length of the book on the shelf with two hands and then utilized that for setting the depth of the desk. One participant found a loophole in the system and placed the footrest above the desk table to use it as a shelf for his stationary (Figure 10c).

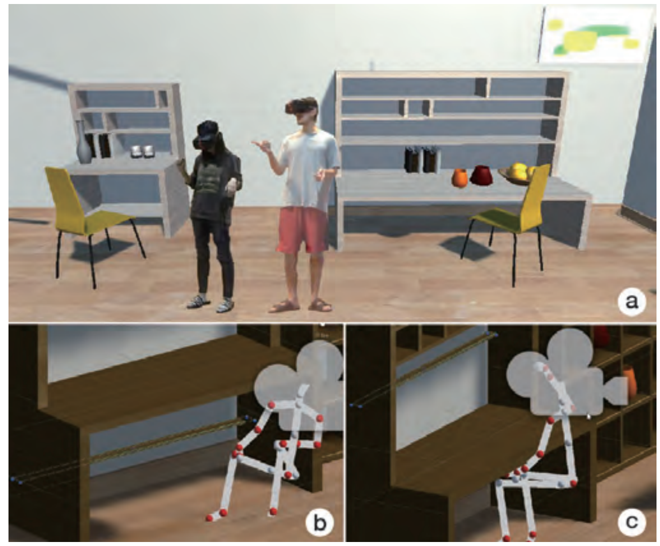


Figure 10. Selected design outputs are illustrated: (a) 3D model from P10 (on the left) and P3 (on the right), (b) original footrest parameter, and (c) creative design from P10 that uses the footrest as a small shelf.

Using Body as an Input for Customization

Throughout the session, we observed participants using the *ruler gestures*, *embodied thinking gestures*, and *acting gestures* dynamically as depicted in Figure 8. This coding reveals the different uses of gestures between participants. *Ruler gestures* were predominantly used by those who valued functional aspects the most (P3, P8): for example, P3 mentioned, *"How well the desk fits my personal items and how efficient this desk is are the most important considerations for me."* Also, these participants were familiar with recalling dimensions from their memory using their body parts. During the interview, P8 mentioned, *"I usually remember various object sizes in terms of the size of my body. So, I am familiar with setting dimensions accurately using my body parts such as my hand span, arm length, or shoulder height, rather than describing these using estimations."* The *embodied thinking gestures* were demonstrated by all participants.

In contrast, participants who frequently use their desk and prioritize a comfortable work experience tried *acting gestures* for the majority of the time to apply personal ergonomic issues (P1, P2, P4, P6, P7, P9, P10). For example, P1 said, *"It was really convenient because I was able to customize my desk at the posture I use every day."* Particularly for the height, participants fully depended on acting gestures (e.g. setting the desk height equivalent to the elbow position).

Figure 11. Selected body postures that participants people used while using BodyMeter. (a)*"I think I can put my things on this shelf."*;, (b)*"I can jump onto the desk if I grab this shelf."*;, (c)*"My design is large enough to relax at the desk like this."*;, (d)*"Oh, this desk is too big to grab things in from the back."*;, (e) *"The height of the foot rest seems okay for me."*;, (f)*"The length should be longer than my reach."*; and, (g)*"The shelf should be at my shoulder height."*

Acting gestures were not only used for specifying, but also for testing and evaluating their design afterwards (P6, P7, P9). This we attributed to the visual feedback. For example, P9 pretended to watch a movie at the desk while reenacting the most comfortable postures (Figure 11c). The participants verified their design decisions through interactions with their virtual desks (Figure 11). These behaviors appeared similar to those used when visiting an offline showroom to test the furniture before purchasing.

Suggestions for Improvements

Although the participants agreed that referring to their body parts allowed them to have a rich experience in customizing their desk, we received several suggestions for improvements. Despite making several iterations in their design, some mentioned that they were afraid to make changes without an undo function. Other participants suggested having *save* and *restore* functionalities in order to quickly switch between design options and perhaps compare options.

Three participants expressed the desire for guidelines to help them equally space the shelf heights. Another user suggested implementing a grid functionality, such as that in *MS PowerPoint*, in order to include this functionality. A related issue arose regarding whether comfort correlates with good posture. Some participants felt they were easily able to make comfortable designs, but had doubts whether their designs were good for their posture. They argued that commercially available products are tested for good posture and general well-being, and that they lack this type of knowledge during the customizing task.

DISCUSSION AND FUTURE WORK

Although our prototype was only tested with a small number of participants on a single product with a relatively low degree of customizability, our study provided insights into how non-professionals think about furniture and how they apply that knowledge in a customization task. The embodied interaction and synergic multimodal commands that were developed indicated to help participants to relate their design decisions to their personal experiences and to exhibit potential to be applied in other design or customization tasks.

Designing with BodyMeter engaged participants in a *reflective* conversation [22] with the design of their desk. As seen in Figure 8, they fluently mixed and iterated through stages of ideation, prototyping, and evaluation. Using their body as input, they posed to find dimensions and evaluated the results through demonstrating future use. The immediate one-to-one scale rendering of the model made the desk experiential, as if it were a prototype. When close to the desk, participants focused on the workspace ergonomics, but when they stepped back and observed their desk from a third person perspective, they made decisions regarding the fit of the desk in the room.

We observed that all participants used their body as *a ruler*, *a means of thinking*, and *a way of simulating*, using scenarios. We argue that recognizing and analyzing these *epistemic* actions [11], in addition to the *pragmatic* (functional) actions to set dimensions, assists in understanding the personalization needs of non-professionals and is useful when developing a design support interface.

The current prototype captures the user's pose and supports the referral of a wide variety of body parts, which proved sufficient for a simple box-based design. However, with more complex designs, subtle hand gestures [31], poses, and exact locations must be captured in order to support the currently ambiguous commands, such as referencing a plane [16]. Several participants mentioned the need for testing their design using work-related objects that they frequently use. A future version of BodyMeter with an augmented reality HMD, such as Microsoft's HoloLens, could further situate the experience in the user's context and include these objects.

The need for design guidance became apparent in the evaluation study. The participants requested guides for aligning or distributing objects, such as those included in 2D layout software. Other participants mentioned the need for personalized feedback on good posture. Because most related works in fabrication focus on creating 3D shapes, they only provide guidance and suggestions on structural integrity [25] and the constraints of manufacturability [23] within the customization task. However, our results demonstrate that providing users with aesthetic and ergonomic guidance is a new avenue that should be explored.

Another venue could be to use BodyMeter with actuated or shape-changing furniture such as TransformTable [24] or inForm [6]. This would enable longitudinal studies on customization behaviors during the product's use. In addition, the decision-making patterns, which were identified in the gesture elicitation study, for adapting furniture to the user's need could be applied to the interaction with future versions of shape changing furniture, particularly the full-body *acting gestures*.

Finally, in this paper, we described a single-user customization process, but furniture is often shared among multiple users, such family members. Therefore, in the future, we will explore how non-professionals can design together.

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