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TOWARDS HANDS-ON COMPUTING IN DESIGN: AN ANALYSIS OF THE HAPTIC DIMENSION OF MODEL MAKING

Çağrı Hakan ZAMAN, Mine ÖZKAR, Gülen ÇAĞDAŞ

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THE COGNITIVE DIMENSION OF MODEL MAKING

Model making plays a crucial part in the early stages of architectural design. It captures spatial percepts and allows for three dimensional thinking and evaluation, hence establishing a direct connection between the body and the object. In the context of architectural design, model making enables exploration of the formal and the spatial qualities of a design through the contrasts in different aspects such as form, size, color or material. The easily revisable nature of the conceptual models helps architects to search for the design alternatives (Knoll and Hechinger, 2007, 19). Architectural scale models are design tools that promote thinking and the communication between the designer and the design (Smith, 2004). Models in the making, aside from serving the material undertaking of a design idea, act as sketches just as two dimensional sketch drawings do. Gürsoy (2010) has recently discussed model-making as a form of preliminary design sketching, and the possible contribution of its inherent ambiguities to the design process. Model sketches are objects in becoming, subject to the designer's spatial perception and intellect. They are continually open to discoveries.

Within the scope of this paper, the point of interest in model sketches is that they contribute not only to seeing but also to touching many possibilities within a design idea. Cognitive studies show that when the three dimensional sense of touch and the sense of vision are used together, perception is faster than when either one is used alone. The sense of touch alone can yield to faster perception of complex forms than the visual one (Jones et al., 2005). Similarly the perception of visual information is directly related to that of haptic information. There are cases where visual perception misleads haptic perception as well as cases where visual perception is weak due to the lack of haptic perception (Reiner, 2008). Haptic feedback improves the quality of discernment in the early phases of object exploration (Moll and Sallnäs, 2009) and touching the objects provides detailed information in comparison with the macro details the naked eye perceives (Reiner, 2008).

In other literature related to design thinking, haptic senses are often observed to be as crucial for creative activities as vision (Prytherch and Jerrard, 2003). Moreover, there is a direct correlation between the development of haptic senses and the experience and practice of crafting skills (Treadaway, 2009). Information that the hands supply to the brain is important for not only the perception of the environment but also the expressive skills of the designer.

In the context of digital design, haptic interaction is considered as a beneficial aspect of the multi-modal process (Schkolne, Pruett and Schröder, 2001). 3D sketches support conceptual phases of design by providing spatial interaction with the design objects as well as enhancing the perception of the scale and the orientation (Israel et al., 2009). Virtual reality 3D sketching improves cognitive abilities in conceptual phases of design (Rahimian and Ibrahim, 2011).

Early stages of a design process are where the designer experiments with the initial concepts and the perceptual qualities of the envisioned design idea. In our contemporary culture of technology, the acts of design performed in these stages are being transferred into the digital domain more and more as design and production processes merge and gain speed. The visual and spatial integrity of design performances in earlier stages has value for the entire design process and should be sustained in the digital domain as well. The value of hands-on design thinking, or in other words the spatial and visual thinking with materials at hand, comes forth in pedagogical discussions that emphasize design reasoning in the field of arts and design as early as the beginning of the 19th century. Considering the literature above, its sustainment today is crucial for the future of design thinking in the information age.

The present study analyzes a limited sampling of different hand movements performed while working on a physical sketch model. Several actions and the movements that are used while performing these actions are identified and classified. The aim is to create an abstract repertoire of model making hand movements for the purpose of digitizing them. This constitutes a first step towards carrying that knowledge and experience to digitized conceptual stages of architectural design processes.

EXISTING TOOLS AND METHODS FOR HAPTIC DATA COLLECTION AND INTERPRETATION

An efficient use of the digital environment in design processes will be possible when senses of sight, hearing, and touch can be integrated with it. Varga (2008) points out that the transfer of design data to computer through one and two dimensional methods is one of the difficulties designers encounter in the computer environment. There are already studies where senses of touch and sight are used either separately or concurrently in a digital environment. In our work, we pursue the study of hand motions in sketch-model making. In building a classified repertoire of these motions, we prepare them for spatial and quantitative interpretation and translation to and from the digital environment.

Several studies on object design show that different tools and methods make it possible to transfer qualities such as texture, volume and flexibility to the models in the digital environment. Among these are studies where probe-like haptic feedback tools, such as PHANTOM, are used for both recognizing and shaping objects in product design. In these, pen-like data tools simulate the sense of touch in the digital environment. Through the pen, the movements of the hand are directly translated to the coordinate system that is digitally modeled. The point that stands for the tip of the pen is the cursor. In this way, it becomes possible to perceive the shape of the digital object and to modify it. However, Evans et al. (2005) show that, in cases where such haptic tools are used in the field of industrial design, point feedback is incompetent in defining smooth surfaces and place restrictions on designs. Similarly, Jones et al. (2005) argued that haptic point probes are limited in the haptic perception of objects since they are not suitable for spatial deformations and lack thermal and kinesthetic cues. These tools can only partially transfer the information of the haptic experience to the digital environment.

The discrete translation of continuous movements is a challenge. A way is to identify a language of the hand movements as a more holistic approach to simulate more than the changing positions of the tip of the pen. An accurate translation of the human hand movements in the physical environment can greatly improve the quality of the designer's relation with the digital environment. Horvath et al. (2003) have developed a language of hand motions (HML) that designers make in defining shapes in the air. In further studies, Varga (2008) produces digital conceptual models using hand movements. These studies, which exclude any haptic feedback, show that a sequence of hand movements produced for certain shapes, can readily be performed by the users and translated to the digital model.

Haptic feedback problems can be overcome by using electronic haptic ware. Haptic gloves and other gears of the same ilk can be effective in translating a hand movement to the digital environment while supplying haptic feedback for the next movement. Our proposed system is geared towards enabling direct manipulation of digital objects in three dimensional space. In order to provide a realistic experience, the use of such haptic ware as interface is key. The focus however is in which information is captured and how it is interpreted, and hence in the effort to understand actions in manipulating a material in hands-on design thinking.

Horvath et al. (2003) observe that the time spent in conventional CAD programs decrease with the help of hand movements, and that the concept models produced as such are more creative and flexible compared to those produced with CAD software. Similarly, Varga (2008) reports that the use of hand motion language in the production of concept shapes does not only trigger creativity but it is also intuitional and entertaining.

The compilation of a repertoire based on hand movements can be used as a tool in producing models in preliminary design processes. For this reason a similar approach was adopted in our present research on the production of architectural sketch models. The repertoire to be produced from the hand movements of the users making models will enable them to work in a similar way in a digital environment.

Defining and classifying simple hand movements has an important potential for enriching the feedback in a virtual environment. Frolov et al. (2008) state that an optimal feedback is possible only by predicting what the user wants to do before touching the object. At this point, our primary question has been how to define and analyze the hand movements in order to predict how the action is realized and to establish a basis for an improved haptic simulation.

To obtain feedback as close to reality as possible, it is ideal if the hand movements are interpreted simultaneously by the computer. The Hidden Markov Model is a method frequently used in speech recognition and recently in processing hand movements (Frolov et al, 2008). When designing a system in which the user supplies a continuous data entry with his hand movements, the Hidden Markov model responses quickly with a stochastic method in selecting and processing these entries. In cases when where it is not easy to decipher what state a system is in, this model makes it possible to predict its subsequent state based on the knowledge of its previous states.

Prompted by the need to understand and sustain the haptic relation between the user and the model in order for it to be transferred to the digital media, the present study provides a theoretical framework to digitally identify the performed hand movements from within a selective repertoire in order to give accurate and appropriate haptic feedback to the user. Technically, it is a preparation to control the incongruities between the user's action and the feedback from the model by identifying the most relevant movements in a given context from among the continuous multiplicity of hand movements.

RECOGNIZING AND COMPUTING THE MOVEMENTS OF THE MODEL MAKING HANDS

The study proposes a repertoire of a limited number of hand movements displayed by designers while acting on a particular material. This repertoire is based on the transforming positions of hands and not the mental representations or idealized claims that designers have of the resulting shapes. It provides an analysis of hand movements used for different functions in different scales and the preliminary step towards more articulate haptic data recognition in the future.

To compile this basic data, short sessions of model making were held with two architects (both graduate students of architecture) as participants. Each participant was observed in three sessions. Sessions were recorded audio-visually in order to capture designers' movements as well as their vocalized thoughts, intentions, and observations.

In the first session, designers were given an abstract concept and asked to make a sketch model within a ten-minute time frame. The concepts continuity and transparency were arbitrarily chosen and assigned, and are assumed not to reflect an impact on the experimentation. The aim in this stage was to identify very crudely the movements the designers made while working on a sketch model without any interference. In an earlier pilot study, a preliminary set of findings was already obtained and gave a general idea regarding what to expect as actions, for instance bending, folding, breaking, tearing, etc. This time around, significant findings were obtained in terms of the differences and similarities between the actions. For instance, we observed that the movements of breaking and bending repeat in different ways, but there are similarities between these movements in terms of the positions of the hands with regards to each other as shown in **Figure 1.**

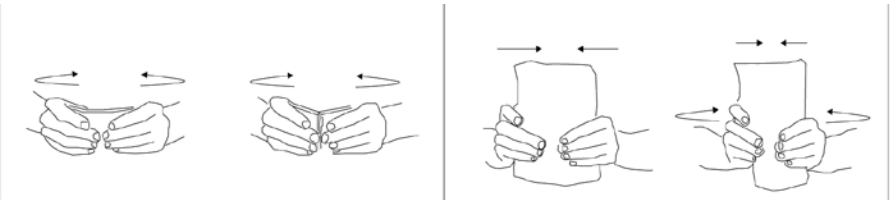

Figure 1. The comparison of the movements in bending and breaking: in both cases, mirrored hands rotate the material oppositely around a central axis whereas in bending the two hands also move closer in order to reduce the strain on the material.

The findings of this stage helped to form a short list of actions to be used as a pregiven guide for the third session where the movements were observed in detail.

In the second session, the participants were asked to touch some objects, and to utter the information they obtained about these. The hand movements used while examining the object of different shapes were identified in this stage.

It was observed that different hand movements were used while examining edged and curved objects. It was further observed that while curved objects were grasped by the hand as a whole while examining, edged objects were perceived mostly with the help of fingers. It was also seen that while perceiving the shapes of all the objects, they were turned around in the hand; fingers were moved back and forth over the objects in order to feel what the materials are made from. This led to the establishing of material constraints and the aspect of scale as a criterion of analysis in the final session. The aspect of scale here refers to whether the movement is in the fingers, the hands (from wrists) or the forearms (from the elbows).

In the final session, certain movements that could be used in shaping the objects were applied on different materials. For this, movements including the actions of bending, breaking, folding, twisting, and tearing were investigated in greater detail. Other actions were turning, pulling, puncturing, applying pressure, placing, tool using, surface exploring, grasping and releasing.

The participants performed these actions on four different materials of different surface qualities and of different hardness. The materials were sheets of aluminum, cardboard, rubber and styrofoam. This stage allowed for the identification of the characteristics of these movements. The hardness and the shape of the materials seem to have a consistent effect on the movements. If the material is harder and the force applied increases, transitions between the stages of the movement become sharper.

A REPERTOIRE OF HAND MOVEMENTS

The findings of the third session constitute the bulk of our research. Various actions were prescribed to the participants in order to observe

Figure 2. Materials given to the participants: sheets of styrofoam, aluminum, rubber, cardboard.

what movements these actions call for when interacting with different materials. Although we observed in the session many different hand movements used in the model making process, a limited number is selected for next steps. Actions span over a wide range of instances including various shape and material surface exploration, and are reduced to a few key instances for the purpose of practicality in the classification. Similarly some actions performed by only a slight change in the position of the hands are difficult to directly recognize and easily identify.

Finally, as a result of the first session findings, we understand that the actions of grasping and releasing play a bigger role in model making than any other action as putting the objects together, placing and fixing them all involve the actions of grasping and releasing. It is predicted that sustaining an efficient recognition algorithm in computerizing this data will particularly be difficult due to their ubiquity as parts of most other actions. More accurate results can be obtained usually if the difference between model movements to be used in the research increases. Hence these actions are left outside the analysis.

In the end, our detailed analysis is limited to a selection of bending, breaking, folding, twisting, and tearing as well as using a particular tool. The reasoning for the selection largely relies on the ease of identification of the beginnings and endings of the movements involved, as well as on the higher frequency of use in the first session, and their comparability to one another in terms of similarities and/or stark differences.

The movements are observed in terms of the directions (the traces of the parts of the hands at the relevant scale) and the duration (and the hence-assumed intensity) of the forces exerted.

The Variable of Scale

Based on the observations from the second session, the way in which the designer engages with the material or the object gives us clues to analyze the movements in terms of three different scales of fingers, hands and elbows/arms.

The movement of bending was observed to be similar across all scales. In other words, in different acts of bending, the participant uses fingers, hands, or forearms but the observed movement traces a similar shape in space.

In the movements of turning and tearing, although there are similarities in shape, the positions of hands vary horizontally depending on the direction of the movement applied in the movement of tearing. The shape and the dimension of the material at hand play a role in the characteristics of the movement. When the material is smaller than a certain size, movements are realized mostly with the fingers. Significant to our analysis, there is little characteristic variation in the transformations of the positions of the fingers and the hands at different scales. Hand parts seem to be tracing the same movements.

It is also significant that some actions are particular to one scale. Grasping for example, although not included in the study, is realized only with minute changes in the relative positions of the fingers which are difficult to determine.

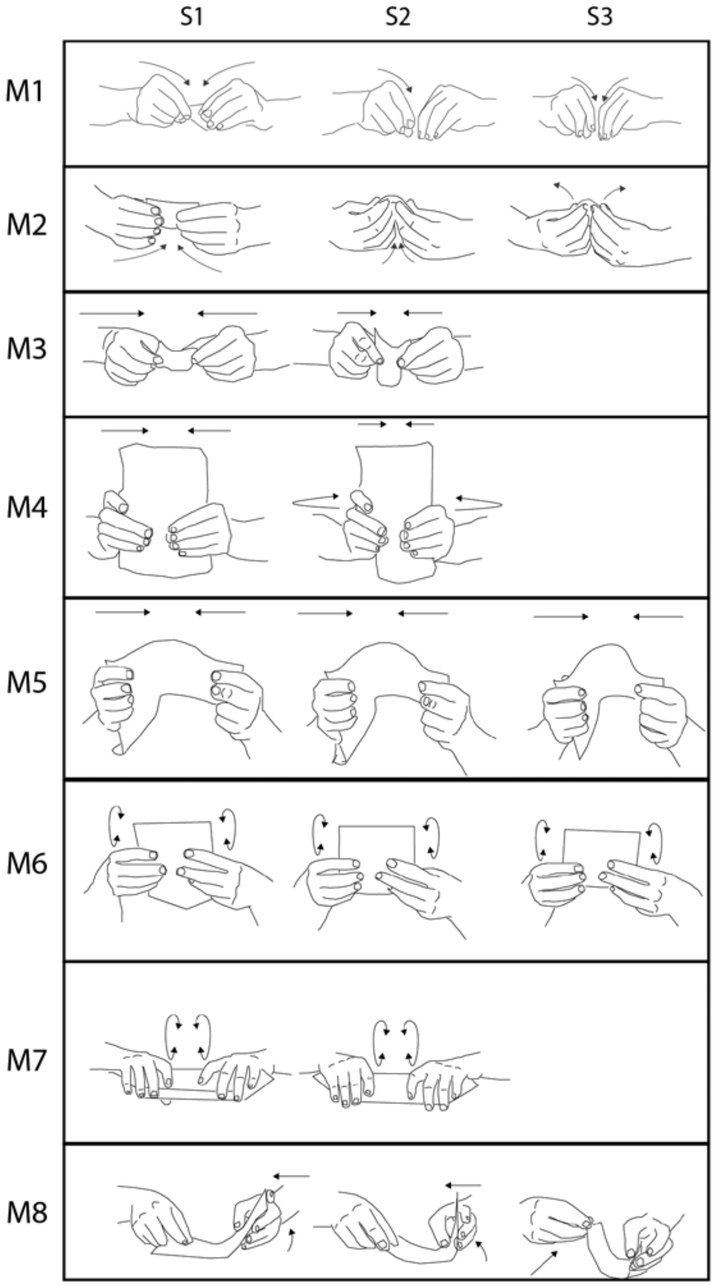

Figure 3. The various instances of bending movement (M1-M8) listed vertically whereas the rows show the sequences performed (S1, S2, etc.) in each movement.

Bending

Together with folding and breaking, bending is the most common action observed in the first sessions. In the third session, when the actions are articulated individually, different movements are observed when the participants are bending different material.

The first type of bending includes the mirrored rotation of hands around various axes (movements M1, M2, M4). In M1 and M2, the rotation is around the same two horizontal axes but in opposite directions. This change depends on the beginning position of the hands. In M4, there is only one axis and it is vertical.

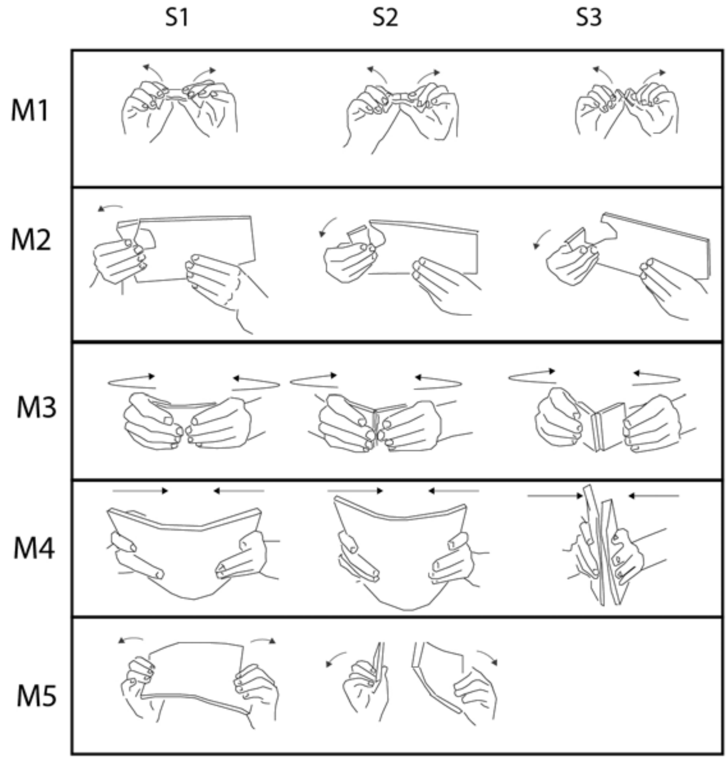

Figure 4. The various instances of breaking movement (M1-M5) listed vertically whereas the rows show the sequences performed (S1, S2, etc.) in each movement. The scale of finger in M1, of hands in M2, M3 and of arms in M4, M5 are employed.

In the second type of bending, hands are moving closer (movements M3, M4, M5). These movements are seen only in soft materials, which are easy to bend. In M4, first and second types of movements are combined. In both types, the scale is that of the hands.

Another type of bending consists of the rotation of the hands in parallel to one another, which can be seen in movements M6 and M7. In this movement, the index and the middle fingers of both hands rotate in the same direction causing a part of the material to bend while the thumb and the other fingers are holding the rest of the material in place. The scale of this movement can be said to be of the fingers.

Lastly, in movement M8, one hand is fixing the material onto the working surface, while the other one rotates from the wrist to bend the material. By default, hands are getting closer. The scale is also that of the hands in this case.

Breaking

As mentioned in previous sections, the action of breaking is quiet similar to that of bending. The first is often an extreme condition of the latter. The difference between bending and breaking gets highlighted with the type of material worked on. Bending time is longer when the material is not brittle.

There are three main types of movements defining this action. The first is the mirrored rotation independent of the working scale of the hands, fingers or arms (M1, M3, M5). The size of the material changes among these instances. Where the material is small, fingers are used and as the material size increases the wrist and elbow movements are more appropriate for applying the required force to break the material.

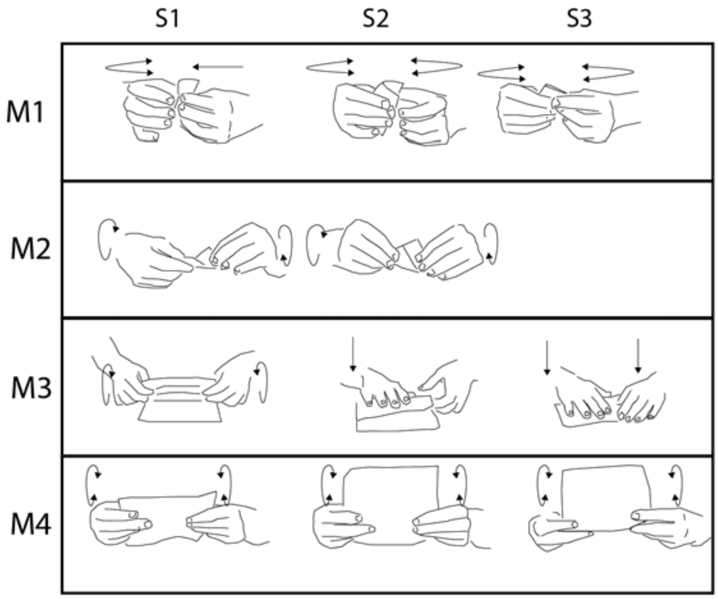

Figure 5. The various instances of folding movement (M1-M4) listed vertically whereas the rows show the sequences performed (S1, S2, *etc.*) in each movement.

In the second type, exemplified in M2, one hand is fixed holding the bigger portion of the material in place while the other hand rotates around an invisible axis to break (off) a small piece of the material.

In the last type, instanced in M4, hands move closer to apply pressure to the material from opposite ends. Different than the movements described under bending, the hands do not rotate from the wrist but the action is in the elbows. In this case, it is noted that the material size is large, and this might, in turn, be the very reason for the designer to keep the fingers and even the hand positions fixed.

Additionally, based on the vocalized observations of the participants, the act of breaking seems to require a marked and strong force implemented at the fingertips. Differently, the act of bending is performed with an extensive force applied all over the fingers or the palms depending on the scale used. This difference designates the scale and the type of movement for the two actions of bending and breaking.

Folding

Although it may sound similar to bending at first, the act of folding turns out to be a more complex procedure than breaking and bending. In the samples studies, one hand is often assisting the other to perform the necessary movements and this assistance is usually to designate a precise axis of the fold. The movements of one hand and the assistance of the other shift from fingers to hand scales based on the material.

In M1, we observe three consecutive steps. In the first step, the fingertips of the assisting hand are delineating the axis for the fold while the thumb and the pointing fingers of the other hand separately guide the opposite sides of the material in opposite directions around the axis. In the following two steps, the assisting finger moves out of the way and the entire hand supports the pressing movement of the other to complete the task.

In M2, the thumbs of each hand delineate an axis for the fold from two opposing sides and the rest of the hands rotate in opposite directions

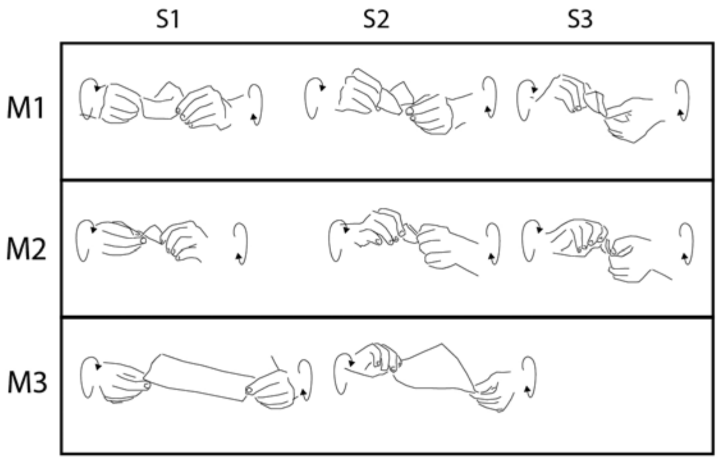

Figure 6. The various instances of twisting movement (M1-M3) listed vertically whereas the rows show the sequences performed (S1, S2, *etc.*) in each movement.

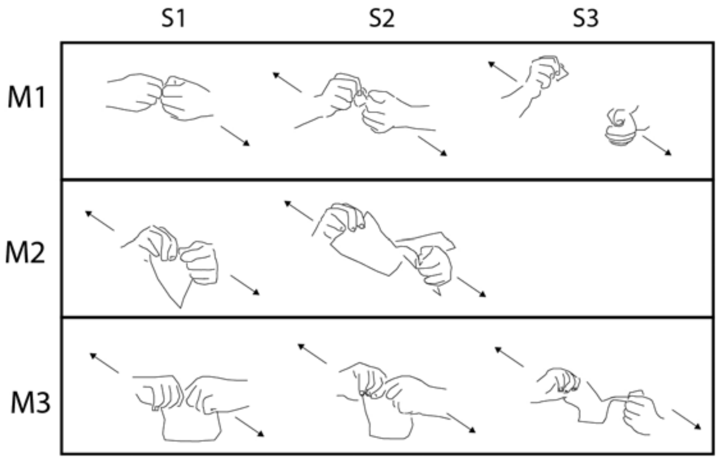

Figure 7. The various instances of tearing movement (M1-M3) listed vertically whereas the rows show the sequences performed (S1, S2, *etc.*) in each movement.

similarly to twisting. Again in a later step, the thumbs move out of the way and the fingers are used to press down the material to complete the folding.

In M3, the hands pick up the material by the ends, making a half circle movement away from the horizontal plane. Later on, one of the hands let go of the edge and press on the bent material at the desired folding axis while the other continues holding the edge. To finish off the action, both hands press on the folding axis horizontally moving back and forth along the axis.

In M4, the index and the middle fingers of both hands rotate around the folding axis while the thumb and the other fingers designate the folding axis and hold the material in the air. This instance was applied to the aluminum sheet. If the material were plastic, the movement would result in bending and if it were a more brittle material, the movement would result in breaking.

Twisting

The action of twisting is always performed in the same way. In all the observed instances, the relevant parts of both hands, whether they are fingers, wrists or elbows, rotate around an axis but in opposite directions. Only in the third instance, M3, in addition to the rotation, the hands get farther apart from one another. This is possibly due to the size and the physical properties of the material.

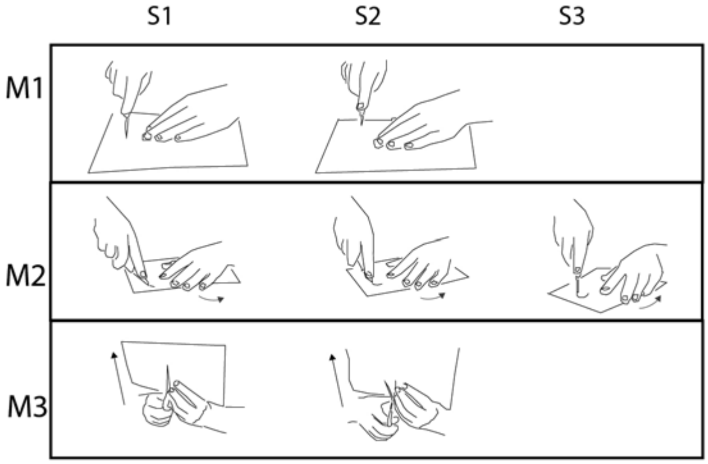

Figure 8. The various instances of the uses of two different tools. In M1 and M2, the tool that is in use is a cutting knife, and in M3, the tool used is a pair of scissors. The sequences of each action (S1, S2, etc.) are also shown.

Tearing

There is only one observed action that defines tearing across all different scales and materials. As hands move in opposite directions away from an axis, a force is applied by the fingertips while the thumb and the index fingers hold the material. Different materials guide the action to be either softer or sharper. In M2, for instance, the material tears more easily than in M3, and less force is applied in comparison.

Using Tools

The tool using action is performed in similar movements for the knife and scissors. One hand always assists the other hand by holding the material stable. In M1, one hand is placed horizontally on the material to hold, while the other makes a straight movement with the knife on the cutting axis. On the other hand, in M2, the assisting hand not only holds the material but also moves and rotates it as needed in order to create the curved path desired for the knife. In M3, differently than in M1 the assistant hand holds the material in the air stable enough for the scissors to move through it.

Classification of the Elements of the Repertoire

It can be seen that while the material and its size change, the fingers, hands and arms performs similar movements. This implies that there are similarities between scales as well as differences. This enables a classification. The table shows the movements and the parameters involved.

A detailed discussion of the table follows in the coming section 'The comparison of the repertoire and its classification with the HML'.

Recognition Schema for Classified Actions

The classification of actions as shown in the table above reveals similarities and differences to be utilized in the recognition process. Below is a preliminary recognition schema based on the classification data. In the tree-like schema, all actions are rooted in the initiation node. Then, step-by-step they are grouped under different properties. For instance, all the actions in the top branch separate into two groups according to whether right and left hands are involved in action together or separately.

The schema is inclusive of indicative properties such as rotation and scale. Nevertheless, there are some limitations. The difference between

ACTIONS INTHREE DIFFERENT SCALES		CLASSIFICATION OF MOVEMENTS									
		Hands separate				Hands together					
						Rotating			Moving		Applying pressure
		Fixed	Assisting	Moving	Rotating	Mirrored	Parallel	Cross	Away	Closer	
BEND	F						M6				
BEND	F						M7				
BEND	H					M1					
BEND	H					M2					
BEND	H									M3	
BEND	H	M8			M8						
BEND	E					M4					
BEND	E									M5	
BREAK	F					M1					
BREAK	H	M2			M2						
BREAK	H					M3					
BREAK	E									M4	
BREAK	E					M5					
FOLD	F		M1		M1						M1
FOLD	F							M2			M2
FOLD	H						M4				
FOLD	E						M3				M3
TWIST	F										
TWIST	H							M1			
TWIST	H							M2			
TWIST	E							M3			
TEAR	F										
TEAR	H								M1		
TEAR	H								M2		
TEAR	E								M3		
USE A TOOL	F										
USE A TOOL	H										
USE A TOOL	E	M1		M1							
USE A TOOL	E		M2	M2							
USE A TOOL	E	M3		M3							

Table 1. Classification of the elements of the repertoire. Movements are the same in some of the actions but the scale is differentiating (eg. Bending M1-Breaking M1).

the actions of bending and breaking is mostly caused by the material and performance time which are factors excluded from the schema. As mentioned before, future work is required to consider performance time as an input in recognition algorithms. Moreover, materials of different degrees of flexibility factor into these two actions. While bending is applicable on highly flexible materials, breaking occurs if the material shows brittle behavior under the applied force. Hence, the characteristic of the forces on the material is another variable to consider.

Comparison of the Forces applied by the Fingertips in Different Actions

As mentioned above, the classification of movements will provide a base for the recognition of actions. Although the movements used in some of the

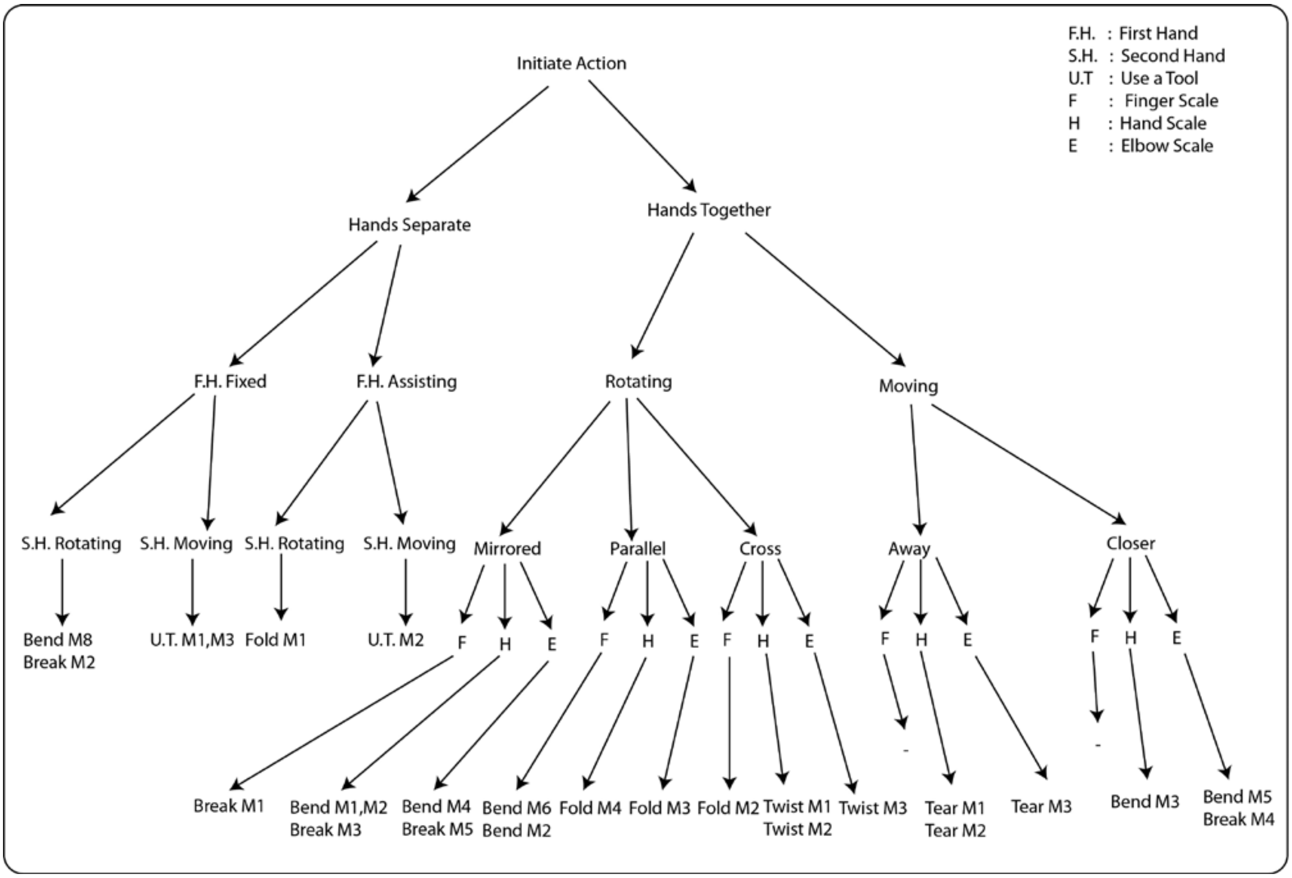

Figure 9. Recognition Schema for all the classified actions.

actions are the same (e.g. Bending M1 – Breaking M3), the performed action is recognized according to the material used. Additionally, the applied forces show variation. Even though it is not complete, one part of our study is the analysis of the forces exerted to materials in different actions. So far, we have been able to compare the forces exerted by the thumb and the index finger of one hand in the actions of bending M1, breaking M3, and twisting M1.

Two sensors are used to capture forces applied by the two fingers in action. These sensors give an output value in a range of 0-1000 when a force up to 4.5 kg is applied.

The sheet size of the materials (styrofoam and rubber) selected for this experiment is 5cm x 10 cm, a constant value for both to prevent misinformation about the forces caused by the size. The action of breaking is performed with styrofoam and the actions of bending and twisting are performed on rubber.

The comparative graphs below each show a 4 second segment of the movements. The exerted force is indicated as the sensor output value increasing downwards on the vertical axis. The vertical grey lines show where the action starts and ends according to visual observations.

Figure 10 illustrates the sudden fall in the value of the exerted force at the moment of breaking. This figure can be said to be generic for breaking action. The thumb is always on the other side of the material and applies more force than the index finger which is supported by the middle finger.

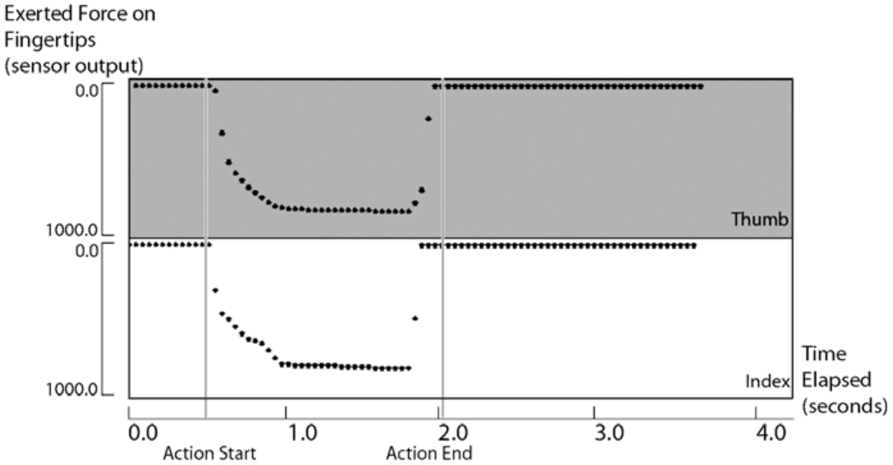

Figure 10. Forces applied for breaking (Breaking M3). The first row is the graph for the thumb and the second row is for the index finger. The applied force is shown in the vertical axis, time elapsed is shown in the horizontal axis.

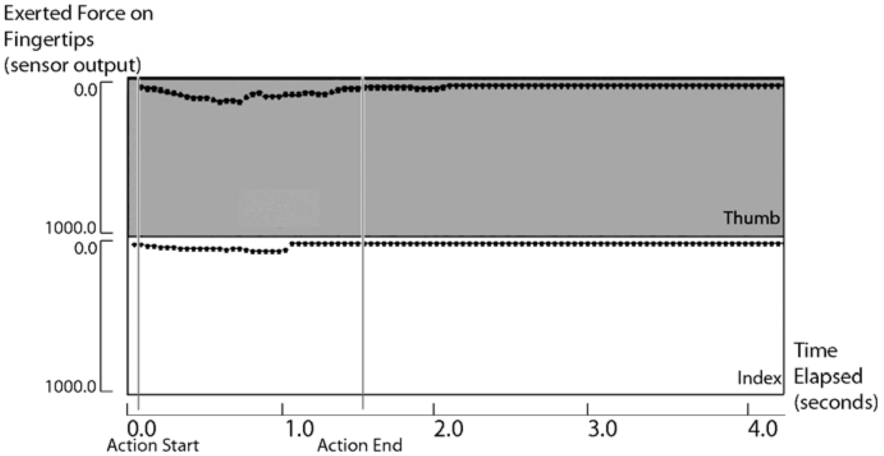

Figure 11. Forces applied for bending (Bending M1). The first row is the graph for the thumb and the second row is for the index finger. The applied force is shown in the vertical axis, time elapsed is shown in the horizontal axis.

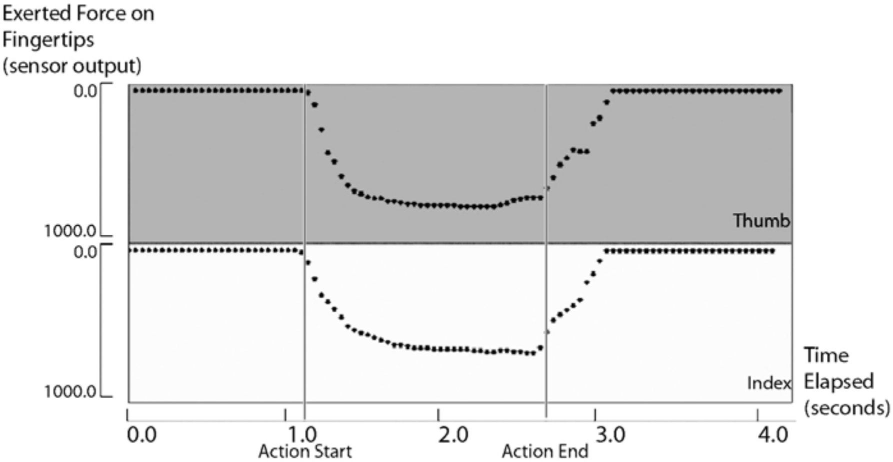

Figure 12. Forces applied for twisting (Twisting M1). The first row is the graph for the thumb and the second row is for the index finger. The applied force is shown in the vertical axis, time elapsed is shown in the horizontal axis.

Figure 11 in comparison with **Figure 10** illustrates that in the action of bending M1, far less force is applied to the material than that in breaking M3 which is visually the same movement type. The figure also shows no sudden fall in the value but a gradual decrease. The force exerted by the index finger is even lower in value and barely captured by the sensor.

Figure 12 shows that the action of twisting M1 has a similar graph to that of breaking M3. Almost the same amount of force is applied to perform this action. It can be seen that the curve of the applied force value is different for twisting. It is of a bell shape unlike the suddenly disrupted curve of breaking. Also its average value is much higher than in the action of bending. Lastly, the action spans differently over the four seconds and lasts longer. The twisting action ends between closer to the end of the third second while there is still a force applied to the material. This prolonged effect is caused by the physical properties of the rubber.

The Comparison of the Repertoire and its Classification with the HML

Comparing the classification obtained through our analysis with the Hand Motion Language serves the purpose of evaluating the research.

Our repertoire, differently than HML, provides information dependent on the changing sizes and properties of materials at hand. While in HML, the hand movements function to define imagined shapes, in the present study, movements are described as functions to modify or deform materials. Whereas in the HML the start and end of each movement is defined by the imagined shape, the end conditions of movements in our case are defined by the tactile engagement of the participants with the material. Also, in our classification, the movements are characterized through the appropriate scales that the participants approach them with, and the sequence of hand movements.

Additional to the intuitive shaping movements in HML, the haptic feedback from the material in our study makes it possible to use the qualities of the material from which the shapes are created as a factor in defining the repertoire. The physical properties of the material and the interaction the participant engages in help identify different types of movements. This aspect comes forth as a new criterion on how to analyze and understand the hand movements in model making. HML is more general whereas our study is dependent on parameters that might have effect on the types of movements performed, such as material properties or scale.

DISCUSSION AND CONCLUSION

As stated at the very beginning, an analysis of certain hand movements performed in model making serves the purpose of interpreting them in digital systems and of establishing the grounds for physical model making actions to be used to produce architectural design models in digital environments.

The present work focused on the compilation of a basic repertoire of movements and their parameters for processing in the digital environment. We observed the actions performed in sample model making sessions and identified a set of recurrences. Then we analyzed and decomposed these actions to basic spatial transformations such as rotation or translation in a table. This enabled us to compare these actions, their parameters such as scale and material properties, and the components of the movement. Thus, we were able to create a schema for the recognition of these movements one by one.

There are a number of specifications that we deem as outcomes to be used for the construction of an algorithm that will recognize and accurately translate the movements to the digital medium.

The classification table in Section 4.8 shows the relation between the actions. The actions of bending and breaking can be performed using the same movements even if the materials are different. The action of folding is completed in several sequences and some sequences are similar to the action of bending. On the other hand, some movements only exist in specific actions. Moving the hands apart from one another is an example of this for the action of tearing. The action of breaking is only applicable to the styrofoam out of the four materials given. Similarly breaking is the only action that is performed on this material; bending, folding, tearing, and twisting are not possible.

The relation between the movements and the materials makes the recognition efficient. One can directly correlate the two so that when either one of them is known, it is often possible to predict the other. This is significant for the algorithm to be constructed to recognize the movements and their sequences.

In addition to this relation between the material and the action, the scale worked is a key determinant. The physical properties as well as the size of the used material play a part in the movement scale. The size of the material directly correlates the scale of the movement; as the material size gets bigger, the scale of the action shifts from fingers to elbows.

The study has a few limitations endured for the purposes of achieving an elemental set of movements. Firstly, as mentioned before, some of the observed actions are eliminated according to their low frequency of occurrence in the sessions and/or the lack of clarity in their visual and audible perception. For instance, unclear movements such as surface exploration are excluded even though their frequency is as high as some of the others. A more complete model-making framework is highly possible if more comprehensive and detailed experiments are set up to acquire more data inclusive of all the varieties of actions observed. Secondly, all movements are defined based on the model making sessions of two participants who were both architects of the same level of expertise. The number, the expertise level and the backgrounds of participants are likely to effect the frequencies and varieties of the actions. Thirdly, the intensity of the forces applied by the designers on the material if documented, as we have shown in 4.10, would be resourceful in the analysis to create more parameters in distinguishing movements in further research.

The next step for this research is to expand and complete the theoretical framework by rendering the repertoire readable with the Hidden Markov Model (HMM) which will enable efficient prediction and quick response. This requires the transfer of the parameters and data into the digital platform and implementing a recognition algorithm. Using a marker based motion capture device will enable us to transfer the spatial data to the computer to be processed according to the schema given in section 4.9 (Figure 9). Such a process would require the construction of a virtual hand and the redefinition of spatial actions. Since the capture system only transfers the positions of determined markers, all other data such as velocity or direction should be calculated using these markers. The system for recognizing items of the repertoire also needs to respond quickly both visually and haptically. Hence not only haptic devices but also visual feedback tools such as cyber eyeglasses will be considered as components of a future application.

Although the compiled repertoire is partial in terms of the criteria given above, in conjunction with the digital environment it is a step towards realizing various applications. The most significant one is the design of digital tools to support the early stages of the design process in which the model making experience is simulated in correlation with the digital environment. This will possibly enable intuited digital models that can at the same time communicate with other CAD software. Additionally, by presenting unlimited options of materials through haptic simulations, some practical problems in making models and experimenting with the materials will be overcome. Many variations such as bringing the models to different scales and changing the materials on the go will be much easier and faster. This type of applications can contribute to architectural education as well as the practice.

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TASARIMDA DOKUNMALI BİLİŞİME DOĞRU: MAKET YAPIMINDA KULLANILAN EL HAREKETLERİNİN BİR ANALİZİ

Tasarımın erken veya kavramsal aşamalarında maketle çalışmak, nesne-beden ilişkisini düşünmeye ve üç boyutlu değerlendirmeye olanak sağlar; görme, dokunma ve hareketleri de içeren mekan algısını devreye sokarak tasarım sürecini zenginleştirir. Mimari tasarımın erken aşamalarının sayısal ortama taşınması, tasarım ve üretim süreçlerinin hızlanıp bütünleşmesiyle giderek yaygınlaşırken, elle çalışmanın getirdiği kazanımların yeni ortamlarda nasıl sürdürülebileceği sorusu ortaya çıkmaktadır.

Üç boyutlu algının görsel algıyı desteklerken yaratıcı düşünceyi de tetiklediğini gösteren çalışmalar, elde maket yapmanın tasarımcıya ve tasarıma bilişsel düzeyde katkı koyduğunu varsaymamıza kaynak olmuştur. Çalışmamızda, bilişsel kazanımların ortamlar arasındaki sürekliliğinin sağlanmasına yönelik bir amaç güdülmüş, maket yapımında gözlemlenen bir dizi el hareketinin sayısal ortama tercümesi konusu ele alınmıştır. Sınırlı bir örneklem ile çalışılarak üç boyutlu eskiz maket yapımında gözlemlenen temel el hareketleri çözümlenmiş, bunların sayısal ortama aktarımında kullanılabilecek soyut bir dağarcık yaratılması ve bu dağarcığın öğelerinin işlenmesine yönelik hesaplama yöntemleri tartışılmıştır.

ÇAĞRI HAKAN ZAMAN; B.Arch
Graduated as architect from İstanbul Technical University, is currently pursuing a master's degree in the Architectural Design Computing Program at the same institute, where he lectures on computer aided design at the Işık University School of Fine Arts. zaman@itu.edu.tr

MİNE ÖZKAR; B.Arch, M.Arch, Ph.D.
Trained as an architect at METU, holds an SMArchS in design inquiry and a PhD in design and computation from Massachusetts Institute of Technology. After employment at METU (2004-2011) and adjunct status at İTU (2009-2011), is currently an associate professor at İstanbul Technical University where she teaches computational theory and design in architecture. ozkar@itu.edu.tr

GÜLEN ÇAĞDAŞ; B.Arch, M.Arch, Ph.D.
A graduate of İstanbul Technical University, Faculty of Architecture, has taught at the same institute since 1981. A professor since 1997, she served as the vice chair to the dean (1994-1997) and as the chair of Architectural Design (2004-2007). Is currently the department head of Informatics, coordinator of the graduate program in Architectural Design Computing, and department head of Architecture. Her main research area is architectural computing. cagdas@itu.edu.tr