TAXONOMY OF GESTURES IN HUMAN COMPUTER INTERACTION

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ABSTRACT

Classification of gestures is important in the area of gestural interaction given the diversity, the complexity and the spontaneity of the gestures in different HCI application domains. Gesture designers for interactive systems as well as state-of-the-art researchers can benefit from a well-structured classification of gestures. Moreover, a taxonomy that includes efficient classes and labels and is capable to effectively distinguish gestures can be employed as a framework to express gestures in reliable gesture recognition systems.

Existing taxonomies either lack a broad scope, or are too abstract and contain ambiguous dimensions.

Proposing a taxonomy of gestures, which can address the diversity in gestural interactions while containing specific dimensions that are capable to distinguish gestures well, is the main contribution of this work.

Evaluation of the proposed taxonomy, which is conducted via an elicitation study, reveals that it can efficiently classify gestures in HCI domain, particularly in the area of mid-air gestures.

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1. INTRODUCTION

Gestural interaction rapidly grows these days. Gestures (especially hand and arm gestures) are very helpful to facilitate interaction with computers due to the flexibility of hand, fingers, arm and other body parts. This flexibility to move in different directions, with different speeds, and different range of movements, can generate various gestures for interaction.

A taxonomy of gestures can provide interactive system designers with different possibilities and variations of appropriate gestures that best fit to their design-oriented intents and purposes while considering real user behaviors and constraints. In addition, a well-established taxonomy of gestures can help HCI researchers have a better understanding of different perspectives of the state-of-the-art research in the field of gestural interaction. Many studies including [1] have addressed the lack of understanding of the design space for gestures.

The aim of this work is to present a taxonomy for gestures in the area of gesture interactions particularly for free hand gestures performed in the 3D space, also known as mid-air gestures. While this taxonomy aims to be broad in order to address the diversity issue, it should be specific enough to avoid being abstract and ambiguous.

The proposed taxonomy is intended to include and to extend the previous works. It also addresses technical issues of recent studies on gesture recognition in modern interactive systems and technologies. For the purpose of improving current gesture recognition frameworks and toolkits, like *Microsoft Kinect* or *Leap Motion* technology [2], which is able to sense and track how you move your hands the way you naturally move them, creating a properly-structured taxonomy is a prerequisite. This taxonomy should necessarily include dimensions that are able to capture different features of gestures to distinguish them well.

Finding and determining appropriate dimensions (attributes) to propose a novel taxonomy is highly critical and the most difficult part of the work. The dimensions which are employed to form the classification should not be limited to a particular application domain. The dimensions should also be specific enough to avoid ambiguity.

As for gesture recognition purpose, I will argue that physical characteristics are very appropriate dimensions to classify gestures. Physical aspects of gestures can nicely represent, code, and even virtually re-generate gestures. Physical characteristics are also able to distinguish and classify gestures to be recognized by computer vision techniques.

Two of the novel physical dimensions that I've utilized in my taxonomy, *Hand Shape* and *Range of Motion (ROM)*, not only can differentiate gestures very well, but also can capture the impacts of constraints on user behaviors. Constraints can change user preferences in performing gestures. My taxonomy addresses this issue as well.

The organization of the rest of this paper is as follows: Section 2 reviews prior works in gesture classification. It begins with earlier classifications which were in the context of linguistics and cognitive science, and then continues with more recent studies and taxonomies of gestures in the field of HCI.

Section 3 describes my taxonomy in detail, the proposed dimensions and categories with their possible values, followed by relative examples to help reader with better intuition.

Section 4 describes how I evaluated my taxonomy via an elicitation study. It also discusses the results and provides with taxonomy breakdown charts and contribution of each value in all dimensions compared to other possible values. Finally, conclusions and future work are explained in section 5.

2. RELATED WORK

In this section, some of the prior works in gesture classifications are mentioned and briefly explained.

It should be noted that gesture has different definitions in different contexts, and hence, the gesture classification which is built upon the gesture definition would vary in different areas. In the area of linguistics and cognitive science, gesture is defined by McNeill (1992) as:

"The spontaneous movements of the hands and arms that we see when people talk." [3]

According to this definition, gesture does not include movement that doesn't accompany speech, whereas in the context of HCI, and in the scope of my taxonomy, gestures can be performed independent of speech and are classified independently. Also, based on the above definition, gesture does not include pantomime, or emblematic gestures such as the *OK* sign in North America, or signed languages such as *American Sign Language (ASL)*, whereas in my classification as well as other classifications in HCI, these kinds of gesture are also referred to as *Pantomimic* or *Symbolic* (see sections 3.2.1.1.2 and 3.2.1.1.3)

My focus in this work is on arm and hand gestures; however, gestures in which head, shoulders, or foot are involved are also considered in the classification. Eye gazes as well as gestures performed by facial expressions are out of the scope of my taxonomy.

2.1. Early Classifications

Early classifications of gestures were at a high level of abstraction, and mostly in the context of linguistics, cognitive science and human discourse studies. In this sub-section, some of the early works on gesture classification are mentioned and briefly explained.

2.1.1. Efron

Historically, the first scholar who did a comprehensive study on spontaneous speech-accompanying gestures was Efron (1941) [4], who studied the linguistic aspects of the gestural behavior of eastern Jews and southern Italians as immigrants in New York City. He wanted to see if/how culture/race affects gestures and body language. Since he was the first scholar who used this terminology for gesture classification, I'll review all of his classes and labels and briefly explain them in this section[1].

Efron proposed two major categories of gestures, according to whether gesture had meaning independent of speech (*objective*), or along with speech (*logical-discursive*).

Objective gestures are the gestures with meaning independent of speech. This type of gesture is identified by the "connotation (whether deictic, pictorial, or symbolic) it possesses independently from the speech of which it may, or may not, be an adjunct". There are three sub-categories in objective gestures:

Deictic gestures are performed "by means of a sign to a visually present object (actual pointing)". Example can be a pointing gesture.

Physiographic gesture represents "either the form of a visual object or a spatial relationship (iconographic gesture), or that of a bodily action (kinetographic gesture)". Efron's example: a speaker says: "so I finally wrote to him". In the meantime, the speaker uses the index finger of one of his hands to write upon the other hand.

S*ymbolic* (or ***emblematic)*** gesture refers to the emblems, such as the *OK* sign in North America. These emblems are necessarily taken from a commonly known vocabulary and have conventionalized meanings.

[1] All quotes in section 2.1.1 are taken from Efron's book [4].

Logical-discursive is the second major category of gestures in Efron's classification, which refers to those gestures that accompany speech. *Logical-discursive* gestures are "a kind of gestural portrayal, not of the object of reference … but of the course of the ideational process itself". "They are related more to the 'how' than to the 'what' of the ideas they reenact". Thus, they represent the process of thought in mind, instead of any physical object. Two subcategories of *logical-discursive* are *batons* and *ideographics*.

Batons are rhythmic gestures that are similar to a conductor's baton, and are used to "beat the tempo of … mental locomotion".

Ideographic gesture is a gesture that "traces or sketches out in the air the 'paths' and 'directions' of the thought-pattern." Efron gives an example: a speaker who shakes his arm in the air between the locations of two mentally-imagined tasks, and then stops it on one of the locations as his conclusion.

While Efron's classification is too abstract for today's applications in HCI and gestural interaction with computers, it opened the road for further studies and his work is considered as a historically significant classification by the community.

2.1.2. Kendon

After Efron, many studies on gestures were conducted. One of the important works, which heavily influenced the following studies, was Kendon's classification [5]. Kendon utilized the term *gesticulation* for what we will typically refer to as gesture. Kendon showed that gestures can be viewed on a continuum of formality and speech-dependency. From least to most formal, the continuum was:

Gesticulation → Language-like Gestures → Pantomimes → Emblems → Sign Languages

In more recent works like Quek's study [6], and Wexelblat's study [7], *Gesticulation* refers to the ordinary natural form that people use in conversations, especially when giving descriptions, and "gesticulation interfaces" (natural gesture interfaces) are the gesture and speech interfaces where gestures accompany speech for a more natural interaction using bare hands. According to this definition, gesticulations rely on the computational analysis (computer vision and pattern recognition) of hand movements and are not based on pre-recorded and pre-defined gesture mapping.

The difference between pantomimes and emblems in Kendon's classification is that movements in pantomime are not a set of conventionalized symbols from a commonly known vocabulary. However, their meaning is still recognizable to the audience. The North American *OK* sign, with thumb and index finger in a circle, while the other fingers are opened and stretched is an example of *emblem*.

Kendon's formality-based classification is of utmost importance because formality pertains to gesture recognition which is critical in recent interactive systems. Gesticulations have the least formality whereas emblems and signs have the most. The less formal a gesture, the more effort is required to accurately recognize and analyze it, due to more uncertainty and ambiguity in gesticulation-like gestures that are not fixed and pre-planned. One of the aims and promises of HCI research, especially AI studies on gesticulation recognition, is to provide users with such flexibility in gestural interaction that old-fashioned interfaces were lacking. As formality of gestures increases, e.g. symbolic gestures, or semaphores (see section 2.2.2.1), and the gestures get less natural, users would have less freedom to perform arbitrary gestures, and this violates HCI research promises that are aimed to facilitate the user's interaction with computers.

2.1.3. McNeill

Following Kendon, McNeill's (1992) researches (and his earlier publications, most importantly [3]), followed later by Wexelblat (1995) [7], and accompanied later by Quek et al. (2002) [6], formed a turning point between the earlier studies and the recent classifications where gestures are studied independent from speech and includes HCI applications as well.

McNeill's first classification (taken from Efron and others) included four types: *Deictic*, *Iconic*, *Metaphoric* and *Beat*. In his later publications (especially with Quek [6]), he has developed his earlier classification.

Deictic gestures are the pointing motions to identify an intended entity. A variant of this, *abstract deictic*, refers to specific locations in 3D space.

Iconic gestures represent a concrete (not abstract) idea. According to McNeill[2], *"*a gesture is iconic if it bears a close relationship to the semantic content of speech*"*. An example is a gesture that accompanies speaker's words: "he tries going up inside the pipe this time", in which the hand rises upwards.

Metaphoric gestures represent an abstract idea and *"*are similar to iconics in that they present imagery, but present an image of an abstract concept, such as knowledge, language itself, the genre of the narrative, etc.*"*

Beat gestures, which is another term for *batons* used by Efron, are synchronized with the rhythm of speech. "Beats are so named because they look like beating musical time… The typical beat is a simple flick of the hand or fingers up and down, back and forth," which "has just two movement phases".

[2] All quotes in section 2.1.3 are taken from McNeill's book, *Hand and Mind* [3].

2.2. More Recent Classifications of Gestures

As Efron's and McNeill's classifications were based on human speech, their categories have a limited applicability to recent interactive systems, like tabletop applications that employ surface gestures [1]. Such kinds of gestures are performed independent from human speech and need updated approaches and attitudes to be classified. Moreover, as the technology grows, the need for utilizing natural gestures and gesticulation increases, and hence capable recognition approaches and tools are required to address this issue.

2.2.1. Wexelblat, Naturalness Issues

Wexelblat (1998) addresses the need for designing and implementing of systems that are capable to accurately recognize natural, non-posed, and non-discrete gestures [8]. Wexelblat degrades the systems that are only able to recognize pre-planned, artificial, posed, and discrete gestures, and refers to them as useless[3]:

> If users must make one fixed gesture to, for example, move forward in a system then stop, then make another gesture to move backward, I find myself wondering why the system designers bother with gesture in the first place. Why not simply give the person keys to press: one for forward and one for backward?

On the contrary, Wexelblat considers the "natural gestural interaction" to be the only useful mode of interfacing with computer systems: "One of the major points of gesture modes of operation is their naturalness. If you take away that advantage, it is hard to see why the user benefits from a gestural interface at all."

In the following sub-sections, I review more recent classifications of gestures in the area of HCI, and gestural interaction with computers.

[3] All quotes in section 2.2.1 are taken from [8]

2.2.2. Karam, A Comprehensive Taxonomy

Reviewing Quek's study (2002) [6], and other works, Karam et al. (2005) attempted to provide a comprehensive, yet abstract, taxonomy of gesture-based interactions in the field of HCI [9]. Based on Quek et al's study on gestures [6] and relying on the idea that gestures within different domains have different forms, they considered four major attributes as classifier: *gesture style*, *application domain*, *enabling technology* (input) and *system responses* (output).

That implies if we consider a particular application domain, then we're restricted within that specific domain in terms of input/output gestures. Next, each of Karam et al.'s taxonomy is explained given it is a comprehensive taxonomy that has utilized and integrated prior works.

2.2.2.1. Gesture Style

This dimension of Karm et al.'s taxonomy categorizes gestures into the following classes:

- ***Deictic***: This class is for gestures involved with pointing to establish the identity/spatial location of an object
- ***Semaphores***: This class establishes a system of signs and clues which can be employed to imply a meaning. Semaphores could be either dynamic or static. Semaphores can be expressed via hand, fingers, arms, head, or other objects and electronic devices, such as a mouse.
- ***Gesticulation***: It's considered as one of the most natural forms of gesturing. This kind of gestures is commonly multi-modal, consisting of hand movements in combination with speech for example. Unlike semaphores, gesticulations are not pre-planned or taught.
- ***Manipulation***: This class establishes a tight relation between hand movements and the object being manipulated. This category is further classified in terms of *Degree of*

Freedom (DOF), such as two-dimensional or 3D gestures. Manipulation gestures are also referred to as *Physical* (e.g. in [1]).

- ***Sign-Language Gestures***: Gestures of this class are based on linguistic signs. Even though they're communicative, they differ from gesticulations since they're pre-recorded.

2.2.2.2. Input

This class is based on the type of input device of interaction. Gesture classification based on input device is further divided into two categories: *Perceptual* (such as computer vision/audio recognition), which doesn't require physical contact and *non-Perceptual* (such as mouse and light pen, touch screens, or surface interaction) which requires physical touch.

2.2.2.3. Application Domain

This dimension is based on the domain to which gestures are applied, including: Augmented and Virtual Reality, Desktop and Tablet PC, CSCW[4], 3D Displays, Ubiquitous Computing and Smart Environments, Mobile Interfaces, Games, Telematics (ICT), Adaptive Technology, Communication Interfaces (human-human style of human-computer interactions), and Gesture Toolkits.

2.2.2.4. Output (System Response)

In this category, gestures are classified based on the system response and the actual result that they lead to, including visual/audio responses and CPU command responses.

Eventually, it should be noted that, even though Karam et al.'s work is a broad taxonomy, it lacks specific dimensions with the ability to capture major features of gestures, like physical

[4] Computer-Supported Cooperative Work

characteristics of the gestures, and hence, can't be utilized as a helpful framework for designers and researchers to design gestures.

2.2.3. Wobbrock, A Taxonomy for Surface Gestures

Wobbrock's (2009) taxonomy of surface gestures [1] is an exemplar classification which attempts to propose broad but specific dimensions to classify gestures of a limited area of applications, surface gestures, and is one of the two works I have utilized as the foundation of my taxonomy.

Wobbrock et al. address the need for a specific classification for surface gestures based on user behavior in order to describe the gesture design space. Whereas most studies consider surface gestures which have been defined by system designers, Wobbrock et al. attempt to have a planned classification for surface gestures that are performed by non-technical users. Gestures which have been identified by designers would form an arbitrary set even though designers try to design gestures in a structured way and reasonable discipline.

The result of Wobbrock's work is an elaborated qualitative illustration of user-defined gestures and the mental models along with their performance. According to Wobbrock et al., their work was the first work which employed users (non-technical), rather than principles, in the development of gesture sets.

To create the user-defined surface gesture set, they have employed 20 non-technical users to do some gestures to perform prompted tasks on a tabletop *Microsoft Surface* prototype. There has also been a subjective preference rating for each gesture. Eventually, the selection process for the gesture set has been based on the evaluation of how many users have done that particular gesture to perform the prompted task. "The more participants that used the same gesture for a given command, the more likely that gesture would be assigned to that command " [1].

2.2.4. Ruiz, A Taxonomy for 3D Motion Gestures

Similar to Wobbrock et al.'s work, Ruiz et al. (2011) have proposed a broad but specific taxonomy [10], for motion gestures, i.e. 3D gestures that are applied on a smart phone (mobile device) armed with sensors. Ruiz et al.'s taxonomy for motion gestures is the second work I've used as a basis for my proposed taxonomy.

Ruiz et al. have employed a group of physical characteristics as the taxonomy dimensions: *Kinematic Impulse*, *Dimensionality* and *Complexity*. Other than *Kinematic Impulse*, which require precise measurement of acceleration and jerk (rate of change of acceleration), I've used their physical characteristics in my taxonomy (see section 3.2.2).

Both Wobbrock and Ruiz have utilized *elicitation study* approach (also called guessability study, see section 4.1) to create a user-defined gesture set.

As I reviewed prior works in gesture classification, it was remarkable that each of them was either too abstract or limited to an application domain (and had a limited scope), and this, in turn, clarifies the need for a comprehensive taxonomy of gestures, which is not only broad to cover all kinds of gestures in various application domains, but also includes specific and concrete dimensions with the ability to capture all influential features of gestures.

3. TAXONOMY OF GESTURES IN HCI

In this section, my taxonomy of gestures in the area of Human Computer Interaction is presented.

3.1. How the Taxonomy Is Formed?

I've utilized two previous works as the foundation for my taxonomy, Wobbrock et al.'s[1] proposed taxonomy for surface gestures, and Ruiz et al.'s [10] taxonomy for motion gestures. I've selected some of the dimensions of these two taxonomies and used it as the basis for my work although I've modified some of the selected dimensions. From Wobbrock's taxonomy, *Form* (modified), *Nature* (similar to Ruiz's, modified) and *Binding* (original format) have been selected. From Ruiz's taxonomy, *Context* (original format), *Temporal* (similar to Wobbrock's *Flow*, original format), *Dimension* (original format) and *Complexity* (original format) have been chosen.

The selected dimensions are important because they have a high degree of impact on the classification of gestures, and are required due to their capability to distinguish between different gestures as well as their capacity to describe major attributes of gestures. In addition to those dimensions, I've come up with four new dimensions, which have not been used before and are all physical and body-centric characteristics: *Body Part*, *Handedness*, *Hand Shape*, and *Range of Motion* (*ROM*).

3.2. The Dimensions of the Taxonomy

In this section, the dimensions of the proposed taxonomy is presented.

Table 1. Dimensions of The Proposed Taxonomy

	Group 1: Gesture Mapping	
Nature	*Manipulative*	Gesture directly manipulates the object
	Pantomimic	Gesture imitates a real meaningful action
	Symbolic	Gesture visually depicts a sign
	Pointing	Gesture points to a specific location
	Abstract	Gesture mapping is arbitrary
Form	*Static*	No motion/change is in gesture
	Dynamic	Motion/change occurs in gesture
	Stroke	Gesture consists of tap/flick(s)
Binding	*Object-Centric*	Location defined w.r.t. object features
	World-Dependent	Location defined w.r.t. world (app. environment)features
	World-Independent	Gesture can occur anywhere. Location can ignore world features
Temporal	*Continuous*	Action/task is performed during gesture; user can see impact of gesture simultaneously
	Discrete	Action/task is performed after completion of gesture; user can see impact after gesture is done
Context	*In-Context*	Gesture requires specific context
	No-Context	Gesture does not require specific context
	Group 2: Physical Characteristics	
Dimensionality	*Single-Axis*	Gesture occurs around a single axis
	Double-Axis	Gesture occurs on a surface, a 2D plane
	Tri-Axis	Gesture involves either translational or rotational motion, not both, in a 3D space
	Six-Axis	Gesture occurs around both rotational and translational axes, in a 3D space

Table 1. Dimensions of The Proposed Taxonomy (continued)

Complexity	*Simple*	Gesture consists of one atomic gesture
	Compound	Gesture can be decomposed into two or more simple gestures
Body Part	*Hand*	Arm is fixed, but palm or fingers move
	Arm	Arm moves (hand moves as well)
	Head	Gesture is performed by head movement
	Shoulder	Gesture is performed by shoulder movement
	Foot	Gesture is performed by foot movement
Handedness	*Dominant*	Gesture is performed by the user's dominant hand/arm
	Non-Dominant	Gesture is performed by the user's non-dominant hand/arm
	Bi-Manual	Gesture is performed using both hands/arms
Hand Shape	*Flat, Open, Bent, Curved, Index Finger, Fist, ASL Shapes …*	
Range of Motion (ROM)	*Small*	Joint rotation is less than 50% of its normal *ROM*.
	Large	Joint rotation equals or is more than 50% of its normal *ROM*

In table 1, the proposed dimensions are categorized into two groups: *Group1: Gesture Mapping* dimensions and *Group 2: Physical Characteristics*.

Among the four newly proposed physical dimensions, *Hand Shape,* which is by definition applicable to hand and arm gestures, and *Range of Motion (ROM)* have a crucial role to describe how a hand/arm gesture is formed and performed by the user while the other two provide supplemental information about the corresponding gesture. Along with the taxonomy, and as the different possible values of the *Hand Shape* dimension, a set of hand shapes which are mostly employed by users to do gestures is provided in this section as well.

Possible values for each dimension come after the title of the dimension in each row. For a particular gesture, it is possible to assign each dimension more than a single value. However, for the sake of convenience of data analysis of experiments, it is preferred for any gesture in the domain to have a single value in each dimension. Below, each dimension is further explained followed by relevant examples.

3.2.1. Gesture Mapping

Gesture Mapping involves how users map gestures to tasks. These include the *Nature*, *Form*, *Binding*, *Temporal* and *Context* dimensions of the gesture, which are described in the next sub-sections.

3.2.1.1. Nature

The *Nature* dimension is at the highest level of abstraction in this classification and describes the mapping of the gesture to the entities and/or the intended task and how they relate to each other. Below, I describe and provide examples of each of the possible values of the *Nature* dimension.

3.2.1.1.1. Manipulative

A gesture is *Manipulative*, when there is a tight and direct relation/mapping (direct manipulation) between the gesture and its impact on the object/entity. For example, moving the arm to the left and right, or up and down, to move an object on the computer screen in the same directions would be a *Manipulative* gesture because the impact of the hand movement is directly mapped to the changing of the object location. In some prior works, this type of gestures is also called *Physical* [1], [10].

Moreover, if the *Nature* of the gesture is *Manipulative*, then the *Nature* dimension also captures how the computer side is affected by the gesture.

3.2.1.1.2. Pantomimic

A *Pantomimic* gesture is a gesture when the user does a very short pantomime to mimic an action to do a task. This pantomime may consist of only a single arm or hand (or other body parts) movement with a particular hand shape (if the arm/hand is involved), like opening the hand and spreading the fingers to mimic *Release*, or may consist of multiple simple atomic gestures, like imitating picking an object first, by putting fingers together, and then moving the arm backward, to mimic throwing the object away (e.g. for "*Delete"* task).

Prior works often refer to this type of gesture as a *Metaphorical* gesture [1] , [10]. Particularly for motion gestures[5], Ruiz et al. define it as: *"The gesture is a metaphor of acting on a physical object other than a phone (a microphone, an old-fashioned phone)"* [10]. While *Pantomimic* term can also capture these kinds of gestures, there are some other gestures which don't fit into this definition. For instance, if the user elevates his shoulders to convey he/she doesn't know something (and needs help) and to trigger *Help* feature on the computer screen, this gesture can't be considered as *Metaphorical* (there is no metaphor), while it is still *Pantomimic*.

As another example in the context of mid-air gestures, if the user imitates kicking an object out with his/her foot to convey "*Delete"* task, it is not a good fit for *Metaphorical* while it is a perfect match for *Pantomimic*. Therefore, *Pantomimic* is a more appropriate term than *Metaphorical* for the purpose of classification.

[5] Ruiz defines *motion gestures* as: *"*Users can gesture with the device, in three dimensions, by translating or rotating the device. We call these three-dimensional gestures motion gestures.*"*[10]

It should also be considered that merely watching the gesture itself is not sufficient to identify the *Pantomimic* nature of the gesture in some cases, because it relies on the user's mental model as well. That means the user's intent to convey a meaning via doing a pantomime and by demonstrating a short story/scenario is a key point to determine *Pantomimic* nature of the gesture.

3.2.1.1.3. Symbolic

The gesture is *Symbolic* if the user visually depicts a symbol such as showing an OK sign, or a thumb-up. Other typical examples are drawing a check mark or a question mark to convey a specific meaning. It is important to notice that the sign could be either commonly known from a vocabulary, which is based on the user's experience and background, or unknown; however, in either case, the gesture has to depict a symbol to be called *Symbolic*. The term *Semaphoric* has also been used for this type in prior works [6], [9].

Symbolic gestures are limited to hand/arm gestures only. Even though it is possible to draw a symbol by head or foot, very few users are likely to use them.

3.2.1.1.4. Pointing

If the user points to a specific location/point on the computer screen, the gesture has *Pointing* nature. In MacNeill's book [3], this type is called as *Deictic*.

3.2.1.1.5. Abstract

The gesture has *Abstract* nature if the gesture mapping is arbitrary. For example, moving the arm to the left to convey *Cancel* is an *Abstract* gesture.

Typically, abstract gestures are employed when there is a limited space of available gestures. Given the potential diversity of gestures in all application domains of HCI, if users and/or designers are aware of possible gestures that can be employed to perform a designated task, there would be fewer abstract gestures with an arbitrary mapping.

3.2.1.2. Form

The *Form* dimension determines whether the gesture includes motion or contains some types of dynamism while performing the gesture. Motion can occur in any of the body parts that are involved in the gesture (e.g. hand, arm, or head), and hence, the gesture would be *dynamic* in this case.

For example, moving the arm to the left and right to manipulate the location of a specific object is a *dynamic* gesture.

If the gesture doesn't include any kind of motion or change while being performed, then it is *static*. Pointing to a particular point on a surface, or showing a thumb-up are examples of *static* gestures.

Also, if a gesture consists of one or more taps or flicks either on a surface or in the air, then it would be in the form of *stroke*. One might argue that *stroke* is just a variation of *dynamic* and doesn't need to be differentiated. While this argument might be true to some extent and they can be considered of the same type, in order to highlight and differentiate gestures which contain only one single or multiple taps or flick-like motions as the action performed, *stroke* comes as a separate form.

3.2.1.3. Binding

The *Binding* dimension determines whether or not the gesture requires particular information either about the object it affects or produces, or about the application environment.

Object-Centric gestures require information about the object location, and hence, location is defined with respect to the object. For example, selecting a specific location on the computer screen by touching or pointing to it would be *Object-Centric*.

World-Dependent gestures are those which need information about the world such as tapping in the top-right corner of the display or dragging an object off-screen [1].

World-Independent gestures, in contrast, require no information, neither about the object they affect nor about world (the application environment), and generally can occur anywhere on the surface (in case the application is tabletop) or any space in the air (for mid-air gestures). For example, nodding as a head gesture to do "*Confirm"* task is *World-Independent* because it can occur anywhere. In the context of tabletop applications, drawing a check mark with the index finger to perform "*Accept"* is also *World-Independent* if it can be performed anywhere on the screen.

Wobbrock et al. also have "mixed dependencies" [1], when a gesture's *Binding* could be different from different perspectives. However, I have removed it from my taxonomy because it makes the *Binding* dimension ambiguous. When a gesture's binding can be interpreted in different ways, the most reasonable and obvious interpretation is considered in my taxonomy.

It should be noted that the user's intent to do an *Object-Centric* gesture is not enough to determine if the gesture is *Object-Centric*. The application at the computer side should also be able to detect if the user aims a particular location and should provide the user with the required information about the object (*Object-Centric*). Similarly, if the user needs to know the screen coordinates to perform a *World-Dependent* gesture, the application should be able to provide the information regarding the application environment so that we can call the gesture

World-Dependent; otherwise, the mentioned gestures would be *World-Independent* despite of the user's intent.

For instance, in the context of mid-air gestures, if the user points to a specific location as the gesture to select it, and the application can sense the user has pointed to that particular location, then the gesture would be *Object-Centric*. However, this is not the case if the application doesn't have that ability and hence, regardless of the user's intent to point to that location, the gesture would be *World-Independent*.

Moreover, it should be mentioned that *Binding* dimension is the attribute of the gesture not the task, although there is a "natural binding" for some tasks. For example, for the task "*Save*", one has no idea whether the gesture that performs the "*Save*" action is defined in such a way that it takes place on an object (*Object-Centric*), takes place with respect to global features (*World-Dependent*), or is neither of these. A user might execute the "*Save*" gesture by double-tapping the top-left corner of the global display, which would make the gesture *World-Dependent*. Another user might execute the "*Save*" gesture by double-tapping a specific "*Save*" object (button/menu, etc.), or by double-tapping the object he has most recently changed making the gesture *Object-Centric*. Good design dictates that the tasks which affect the entire world should have gestures that are *World-Dependent*, they don't have to be though. Similarly, good design dictates that the tasks which affect only individual objects should have gestures that are *Object-Centric*. That's just a natural mapping, not an inherent aspect to this concept.

So, in some cases, there might be a sort of "natural binding" that is suggested by the nature of the task. But in the end, the *Binding* dimension is still a property of the gesture, not the task. It's just that for some tasks, certain gestures make the most sense binding-wise.

3.2.1.4. Temporal

The *Temporal* dimension (called *Flow* in Wobbrock's classification [1]) deals with the relation between the gesture recognition and its impact. A gesture is classified *Discrete* if the impact of the gesture occurs after the gesture is completed. In this case, respond to the gesture is event-driven, similar to when an event occurs in an *Object Oriented Programming* application (like a C#.NET application). Once a *Discrete* gesture is performed, it will be delimited and recognized by the computer and then will be responded. For example, when a user shows "thumb-up" to "*Confirm*" an action, after he does the gesture and the computer recognizes the hand shape, the action will be confirmed, and hence, the gesture will be *Discrete*.

On the contrary, *Temporal* dimension is *Continuous* if the recognition of the gesture by the computer is done as an ongoing process while the gesture is performed, and we can see the gesture's impact as it is in progress. An example of a *Continuous* gesture is when a user moves his arm to the left and right to navigate a map to the left and right. As he moves his arm, we can see the map navigates to the same direction.

Manipulative gestures are typically *Continuous* because there is a feedback loop between the human and the computer, and we can see the gesture's impact on the entity at the computer side as it progresses.

3.2.1.5. Context

The Context dimension describes if context is needed to determine the meaning of the gesture. If a user performs the same gesture for two or more different purposes/tasks, then the gesture is *In-Context*; otherwise, there would be *No-Context*. For example, if a user draws an "*X*" to "*Delete*" an object, also uses this gesture to "*Cancel*" an action, then the gesture would be *In-Context*.

In order to make gesture recognition and delimitation more convenient and precise, it is preferred to use a gesture for a single task as long as the design space has enough gestures to provide. As mentioned in the previous sections, one of the major purposes of classifying gestures in HCI and conducting elicitation studies to create user-defined gesture sets is to provide the designers with the opportunity to observe the design space and different possibilities and forms of gestures for a particular task in advance.

3.2.2. Physical Characteristics

Physical Characteristics involve physical attributes of the gestures themselves and include: *Dimensionality*, *Complexity*, *Body Part*, *Handedness*, *Hand Shape*, and *Range of Motion (ROM).*

As mentioned in the previous sections, one of the critical shortcomings of the existing taxonomies is lack of dimensions containing physical descriptions that can be employed in order to make gesture classification obvious and specific enough to be understood by designers and researchers. Ruiz et al.'s work deals with *Kinematic Impulse* as a physical characteristic in the classification. However, it requires precise quantitative measurements of acceleration and jerk (rate of change of acceleration) of the device in hand, and hence, is difficult to understand and measure. If precise measurement tools are not available, clear and specific criteria should be defined to determine values for the dimensions that are related to physical characteristics.

3.2.2.1. Dimensionality

According to Ruiz et al.'s classification, "the dimensionality of a gesture is used to describe the number of axes involved in the movement." [10] If a movement consists of both rotation and translation in the 3D space, it is a *six-axis* movement. If only either of translation or rotation occurs in a gesture which is performed in 3D space, it has *tri-axis* dimensionality. If the gesture is performed on a surface, for example on a tabletop application, then the gesture has *Double-Axis* dimensionality. No matter the gesture is done in the mid-air context or on a surface, if the movement is done only in one of the three coordinates, *X*, *Y*, or *Z*, it is *single-axis*.

Among the surface gestures in the area of tabletop applications, the gestures which are touch-based, i.e. those which require direct touch between the surface and the hand during the gesture, *Tri-Axis* and *Six-Axis* movements are impossible, and the dimensionality can only be *Double-Axis*.

In Ruiz et al.'s study of motion gestures, "many gestures, including flicks and flips of the phone involve single-axis motion. Others, for example zooming using a magnifying glass metaphor, require users to translate the phone in 3D space." [10]

In the context of mid-air gestures, even though the gestures are done in 3D space, it is still possible to have single-axis motions as long as the user intends to do the gesture in only one direction (axis), *X*, *Y*, or *Z*. That means slight deviation of an axis is ignored in mid-air gestures. For example, if the user intends to move his arm to the left and right to do "*Pan*" to left and right, each of the movements would be in single-axis despite of slight deviation in the path.

3.2.2.2. Complexity

The *Complexity* dimension describes if the gesture consists of a single *Simple* gesture, or includes multiple *Simple* gestures. *Simple* (atomic) gestures as those which consist of a single motion or posture without repetition, spatial discontinuities like inflection points, and pauses in the middle. According to this definition, any gesture which can be decomposed into two or more *Simple* (atomic) gestures is referred to as a *Compound* gesture.

For example, if a stroke gesture like tapping on a screen is done twice as a single gesture to convey a specific meaning, then the gesture is *Compound* because the number of taps matters in this case even though both strokes are the same.

Also, if a hand gesture consists of two or more *Hand Shapes* (see section 3.2.2.5) along with an arm movement, like moving the arm upwards first, and then opening the hand to mimic release, then the gesture is *Compound*. However, the gesture would be *Simple* if changing the hand shape occurs during the arm movement, like opening the hand while moving the arm ahead.

3.2.2.3. Body Part

The Body Part dimension describes which part(s) of the body is/are involved to do the gesture. Even though I've focused on hand and arm gestures in this study, head, foot and shoulder are also considered as the body parts that can be involved in the gesture classification.

It is important to note how arm and hand gestures are differentiated. To make it very clear what exactly the difference between hand and arm gestures is, their definitions come in this section. If the arm moves, the hand definitely moves as well. Therefore, those gestures that contain arm and hand movements together are considered as arm gestures even though hand shape is considered for this type of gestures. For example, "*Pan*" to left and right can be done by moving the arm to left and right with various hand shapes (e.g. index finger or a flat hand). So, hand shape matters in arm gestures to identify how the gesture is performed.

However, it is possible for arm to be fixed while the hand (fingers or wrist) is in motion. So, the gestures in which arm is steady but fingers are moving are considered as hand gestures in this classification. An example is doing "*Release*" task just by opening hand without moving arm.

3.2.2.4. Handedness *(only for hand/arm gestures)*

The Handedness dimension for hand/arm gestures describes whether the user's dominant hand has been used to perform the gesture or his/her non-dominant hand or both hands are involved to perform the gesture. If a hand/arm gesture is performed by the user's dominant hand, the gesture's *Handedness* dimension would be *Dominant*. By the same token, if the gesture is performed by the user's non-dominant hand, the gesture's *Handedness* dimension would be *Non-Dominant*. If both hands (arms) are involved to perform the gesture, it would be a *Bi-Manual* gesture.

Typically, non-dominant hand is used as the reference hand in the gestures which requires both hands involvement. For example, in the context of imaginary interfaces [11], the user can hold his left hand (assume it's his non-dominant hand) with *ASL-L* hand shape (see section 3.2.2.5) to act as the coordinate system, and then moves his right hand (dominant) to draw a chart. This gesture would be a *Bi-Manual* gesture.

3.2.2.5. Hand Shape *(only for hand/arm gestures)*

The *Hand Shape* dimension of a hand/arm gesture describes the configuration, form and posture of fingers while the gesture is performed. *Hand Shape* is one of the key characteristics of my taxonomy and is able to distinguish different hand and arm gestures very efficiently. Hand shape use in tabletop gesture interaction has been studied in [12]; however, according to my investigation during the time of this study, it has not been employed before, neither as a dimension for a taxonomy, nor for studying mid-air gestures.

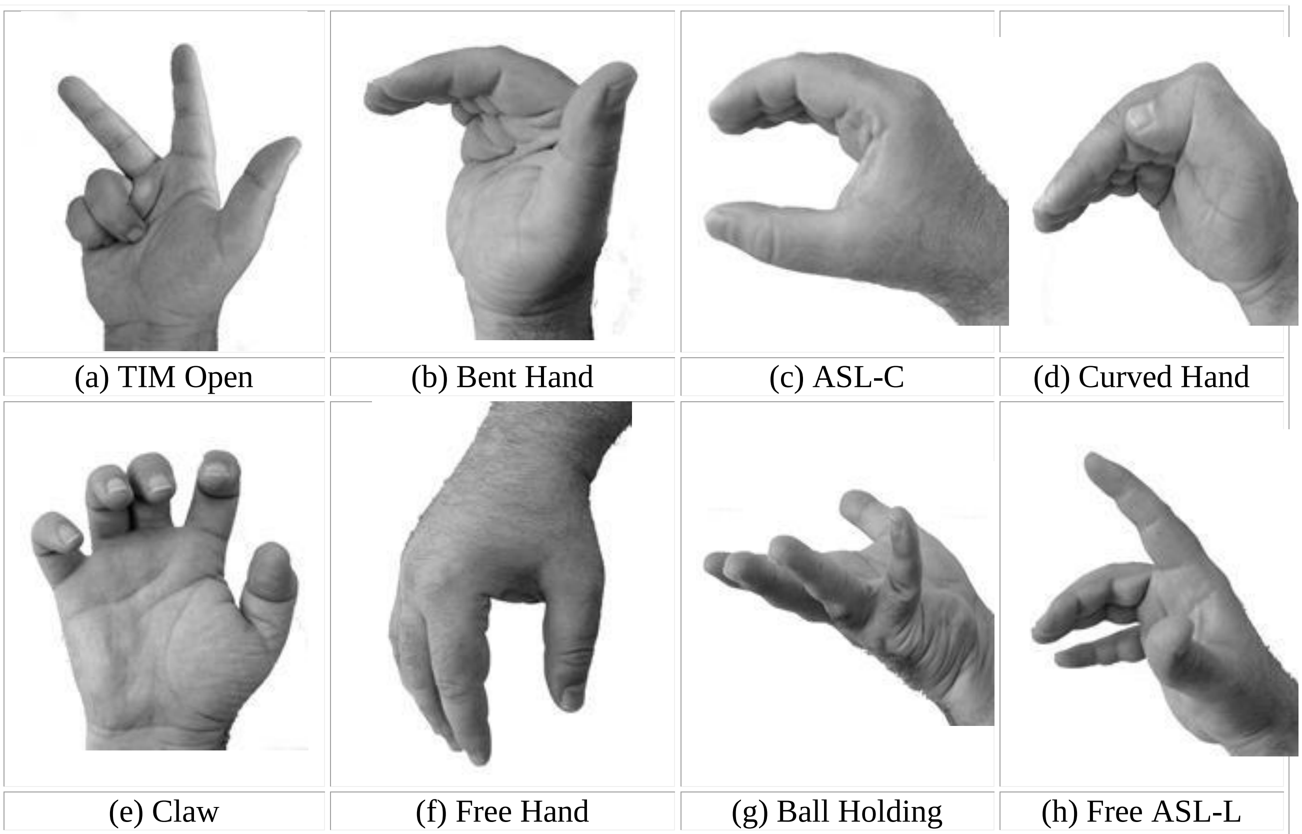
In the elicitation study (containing 756 different mid-air gestures) that is used for evaluation of my taxonomy (see section 4), it has been observed that each participant tends to use one hand shape more in most of the gestures he/she performs. Moreover, when the participants are told that it is preferred to design different gestures for different tasks, one of the common things they consider first is changing the hand shape to generate a new gesture.

Figure 1. Anatomy of Hand [13]

Also, there are several studies for hand postures estimation, recognition and analysis which make it reasonable to use hand shape as a classifier [14], [17], [18].

There are various possibilities for human hand shapes due to its anatomic features (see Figure 1) which enable fingers to pose in different states as well as to rotate and move in different directions, and hence there are diverse combinations of finger configurations which make various unique hand shapes. However, not all of the hand shapes are convenient to form by computer users. Some configurations are even unfeasible due to the limitations in finger joints [18]. Intuitively, those hand shapes, which are easy to work with, are more common to perform gestures among users.

Figure 2 provides a set of common hand shapes among users for gestural interaction with computers. American Sign Language (ASL) names are employed to name a few of them.



(a) TIM Open, (b) Bent Hand, (c) ASL-C, (d) Curved Hand

(e) Claw, (f) Free Hand, (g) Ball Holding, (h) Free ASL-L

Figure 2. Set of Common Hand Shapes

Figure 2. Set of Common Hand Shapes (continued)

It should be noted that each of the hand shapes can occur with different palm orientations as well as arm and wrist positions, and yet all would be the same hand shapes, except for "*Thumb-Up*" and "*Thumb-Down*" which come as two separate hand shapes despite of their similar shape, because they are common signs in symbolic gestures.

As an example to clarify this point, one can use "*Index Finger*" hand shape, Figure 2(m), while his arm is down (or up), also, with different palm orientations, or he can bend his wrist, and all of those configurations would still be similar hand shapes although they can be differentiated by those features. The more features we apply, the more complex the classification would become. Details about different configurations of hand gestures are required to the level that can be beneficial to differentiate the gestures effectively.

3.2.2.6. Range of Motion (ROM)

Range of Motion (ROM) and Hand Shape dimensions are the major contributions of my taxonomy. Before explaining this dimension of the gesture taxonomy, some anatomic terms and definitions should be mentioned. In the context of human anatomy, joint *Range of Motion (ROM)* is defined as:

> The motion available at any single joint and is influenced by the associated bony structure and the physiologic characteristics of the connective tissue surrounding the joint. Important connective tissue that limits joint range of motion includes ligaments and joint capsule.[19]

Each joint in human skeleton has a "normal range of motion"; also called *Expected ROM*. Physiology and physical therapy experts can measure range of motion of a specific joint by means of an instrument called *Goniometer* that measures joint range of motion in the unit of degrees. “Early reports of the procedures for the examination of range of motion (ROM) suggested using visual approximation.” [19]

As a dimension in the gesture taxonomy of this study, *Range of Motion (ROM)* is defined as the ratio of the movement of the corresponding joint, which is attached to and is in charge of moving the involved body part of the gesture, over the *Expected ROM* of that particular joint, and has two values: *Small* (less than 50% of the *Expected ROM* of the joint) and *Large* (50% or more of the *Expected ROM* of the joint).

For any gesture, the involved body part and the corresponding joint should be determined first, to evaluate *ROM* in the gesture classification (*Small/Large*). Since visual observation and approximation is used in this study, *Middle* value for *ROM* has been removed (due to imprecision of observation and approximation) to make the approximation more accurate. However, if the range of movement for each gesture is precisely measured with *Goniometer* or other technical tools, it is possible to have three levels of *ROM* in the taxonomy (say, less than 30% as *Small*, between 30% and 70% as *Middle*, and more than 70% as *Large)*.

As an example, if the gesture is moving the arm to the left to do “*Drag to Left*” task, the corresponding joint can be either the elbow or the shoulder. Let’s assume the arm moves from the elbow joint, then the *Expected ROM* of elbow is approximately 140° [19]. Now, if the user moves his/her arm less than 70° to do the gesture (which may be measured by visual approximation), *ROM* would be *Small*; otherwise, if it is 70° or more, *ROM* is *Large*.

Expected ROM (for *flexion*[6]) of shoulder, elbow and wrist joints, within the age range of 20-54 years, are given in Table 2. The values are taken from [19].

Table 2. Expected Range of Motion (flexion) for shoulder, elbow and wrist

Joint	**Expected Range of Motion(*ROM*)**
Shoulder	165° ± 5°
Elbow	141° ± 5°
Wrist	75° ± 7°

[6] "*Gray's Anatomy* defines *flexion* as occurring when the angle between two bones is decreased. In other words, during flexion, the two bony levers move around the joint axis so that the two levers approach each other." [19]

4. EVALUATION OF TAXONOMY

In this section, I describe how I used an elicitation study to evaluate the effectiveness of my gesture taxonomy. The organization of this section is as follows:

First, in section 4.1, the elicitation study, the participants, the procedure (the way how the experiments were conducted), the three conditions under which the experiments were performed, the analysis method and the results are described. Finally, the discussions based on the results of the study and how I used the data analysis to evaluate my taxonomy are explained in section 4.2.

4.1. Elicitation Study

In the context of *Participatory Design*, eliciting input and feedback from users is a common approach:

> Leaving out the users isn't just undemocratic-it has serious consequences…for the work process and the bottom line. In the mid-1980s, research in the area of user-centered design pointed out the need for applications that were not just user-friendly, but rather were more deeply rooted in the practices of people using them. During this period, studies from the field of human-computer interaction have played an important role in bringing the social sciences and humanities into the formerly quantitatively-oriented system development process [20].

The approach of prompting participants to design and perform gestures for interaction with computer has been used in prior works including Wobbrock's study [1] and Ruiz's work [10].

According to Wobbrock, merely relying on skillful designers would result in somewhat arbitrary gesture sets whose members may be chosen out of concern for reliable recognition [21], whereas applying participatory design principles on the process of designing gestures addresses the following questions:

> What kinds of gestures do non-technical users make? In users' minds, what are the important characteristics of such gestures? Does number of fingers matter like it does in many designer-defined gesture sets? How consistently are gestures employed by different users for the same commands? [1].

As McNeill implies: "Indeed, the important thing about gestures is that they are not fixed. They are free and reveal the idiosyncratic imagery of thought" [3].

Below, I describe an elicitation study conducted by Dr. Daniel Vogel[7] at the University of Waterloo. This is followed by the analysis I performed using the videos recorded and collected by Dr. Vogel, to evaluate my proposed gesture taxonomy. Dr. Vogel performed this experiment to investigate the impact of fatigue as a constraint on how participants change their design of gestures. He recorded the experiment sessions while the participants were designing and performing the gestures to do the prompted tasks. Later, he provided me with the videos and I've used them to evaluate my proposed taxonomy as described in the next sections.

4.1.1. Participants

An elicitation study was conducted (by Dr.Vogel at the University of Waterloo), with 14 paid participants, 7 females and 7 males, all right-handed, selected from university students.

4.1.2. Procedure

In the beginning of each experiment, the participants were given instructions to design and perform gestures, with any part of their body they wish to use, to do 9 different tasks within two different applications (totally 18 tasks).

[7] http://hci.uwaterloo.ca/people

The participants were asked to stand in front of a screen and then, were shown the two application's tasks respectively.

One of the two applications was a *Map* application, and the other one was a *Grid* application for navigating and re-ordering some objects. Table 3 represents all the 18 tasks of these two applications.

The "*Pan*" to left and right was merged into one task "*Pan Left/Right*"; so, the participants performed one gesture to do them. It was also the case for "*Pan*" up and down, as well as for "*Cursor*" and "*Drag*" to left/right, and up/down.

Table 3. The Two Applications and The 18 Tasks of The Elicitation Study

Application	Task
Map	Pan Left / Right
	Pan Up / Down
	Zoom In
	Zoom Out
	Cursor Location
	Select Location
	Help
	Confirm
	Cancel
Grid	Cursor Left / Right
	Cursor Up / Down
	View Description
	Select
	Drag Left / Right
	Drag Up / Down
	Delete
	Release
	Undo

The participants were also told that there was no wrong answer, but it was very important to think out loud while designing the gestures. The participants were asked to perform each gesture they design four times. A custom software, written in C# by Dr.Vogel, was used to track and detect their movements; however, the participants were told not to be concerned whether their movements could be accurately tracked by the software or not. The software was not able to track eye movements, and the participants were informed in advance regarding this.

4.1.3. Conditions

Each experiment was repeated under three conditions. The first condition was standing freely in front of the screen while performing the gestures. The second and the third condition were exactly the same: standing in front of the screen and performing the gestures while two weights were wrapped on their both wrists to help them pretend they were bored after working and interacting with the applications in a public place for a while. They were repeating the gestures they designed to do the 18 tasks under each of the three conditions.

4.1.4. Analysis Method

Now, the analysis method and the results of the experiments are described. In the analysis phase, I watched all the recorded videos of the 14 experiments. The recorded videos were coded for each dimension of the taxonomy. There were totally 756 gestures that were coded (14 participants × 2 applications × 9 tasks × 3 conditions), each of which contained the values for the dimensions of the taxonomy.

To code the gestures, I watched the videos recorded during each experiment session for each participant. I used a MS Excel spreadsheet to include the coded information. As a sample, part of this spreadsheet including the coded data for P1, the first participant, comes in the Appendix.

As can be seen in the sample spreadsheet, I've summarized participant's actions for each task in one or two sentences. Then, by watching the user body movements several times, I coded these movements as a single gesture in terms of different dimensions of the taxonomy. For example, if the user has moved his right arm and hand to the left and right, to do *Pan to Left/Right* task, I've observed how his hand shape was like during performing the gesture (as for the *Hand Shape* dimension), as well as whether it has been a small movement to capture *ROM* dimension and fill the spreadsheet accordingly.

For arm and hand gestures, the *Hand Shape* dimension was determined by observation. The following points have been considered in determining hand shape for each of the 756 gestures in the study:

(a) If both hands are involved, the hand shape of the non-reference hand which does the major work (usually the dominant hand) is considered.

(b) In many gestures, hand shape changes during the gesture. The user starts with a hand shape, and then, during performing the gesture, he/she changes the hand shape. For example, to do "*Release*" via a pantomimic gesture, a user opens his closed dominant hand, which already had a Fist hand shape, i.e. Figure 2(r), to mimic releasing, so the final hand shape would be Open Hand, i.e. Figure 2(w). In such situations, the second hand shape, which is more important and the gesture is built upon, is considered as the hand shape dimension of the taxonomy. It is possible, however, to consider both hand shapes in such situations although data analysis would become more complex.

(c) In hand gestures in which the arm is fixed, forming a particular hand shape requires movement of fingers, and hence the gesture would be dynamic. However, if the gesture is symbolic and only consists of showing a fixed sign with a static hand shape and without moving fingers during the gesture, like showing a thumb-up, then the gesture is considered as static. This is not the case for drawing a check mark though (or question mark, etc.), when moving fingers is required to draw the sign, and the gesture would be dynamic in such situations.

(d) Slight differences between similar hand shapes should be considered. In Figure 2, notice the difference between *Flat Hand* (j) and *Open Hand* (w). In (w), all fingers are separated from each other whereas in (j), only the thumb is detached from others, and other four fingers stick together. Also, notice the differences between *Curved Hand*, *Bent Hand*, *ASL-C*, *Claw* and *Free Hand*. Specifically, *Free Hand* occurs when a person is standing relaxed and his arms are down and free. In this situation, when the person doesn't consume energy to change his hand shape or to stretch fingers, and due to the anatomy of hand, fingers tend to bend slightly. *Free Hand* shape is different from *Bent Hand*, in that the person shapes his hand by bending all fingers except thumb deliberately. *Bent Hand*, in turn, is different from *Curved Hand*, in that all fingers including thumb are joined and curved together.

The reason for considering head, shoulder and foot as the possible values of "*Body Part*" dimension, is that, during this elicitation study that I've used for evaluation of my taxonomy, some gestures have been performed by head, shoulder or foot. Sometimes, the participants used more than one body part to perform the gestures, like head and shoulder together, or hand and arm together (which is categorized as an arm gesture). Thus, gestures of head, shoulder and foot are also considered in the analysis.

4.1.5. Results

After coding the 756 gestures, using *R* scripts, the data was analyzed. For all the 18 tasks, and for each dimension of the taxonomy, the contribution of each of the possible values compared to others is shown in Figure 3 to Figure 13. In this part of analysis, only condition one (hands are free and without weights) is considered. Below, the results of taxonomy breakdown are given for all dimensions.

4.1.5.1. Nature

Figure 3 shows the *Nature* dimension breakdown. The following points are observable:

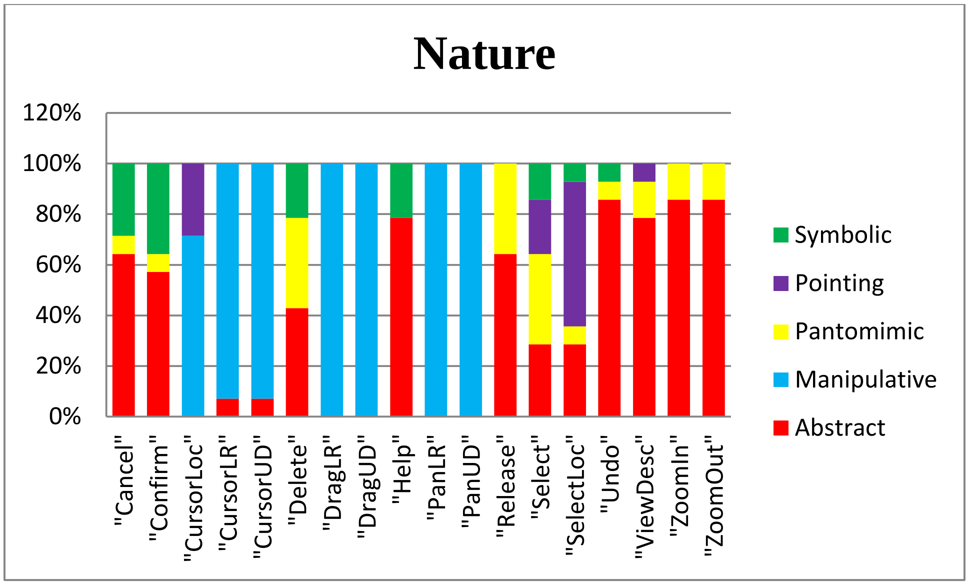


Figure 3. Nature Dimension Breakdown

- There is an inherent relation between the task and the nature of the gesture. "*Cursor Left/Right/Up/Down*", "*Drag Left/Right/Up/Down*", and "*Pan Left/Right/Up/Down*" are almost all performed by manipulative gestures.
- The highest rate of pointing gestures is in "*Select Location*", "*Cursor Location*", and "*Select*" tasks respectively.
- The highest rate of abstract gestures is in "*Zoom In/Out*" and "*Undo*" tasks respectively, for which users typically don't have a clear and familiar mental model.

4.1.5.2. Form

Figure 4 shows Form dimension breakdown. It is remarkable that most gestures are dynamic. Also, stroke gestures are mostly used for the tasks involving "*Select*".

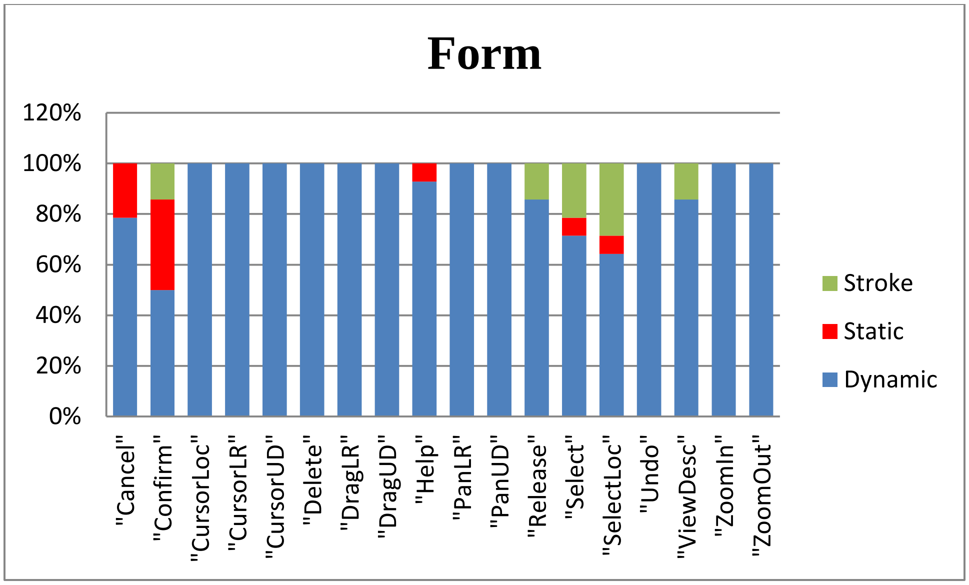


Figure 4. Form Dimension Breakdown

4.1.5.3. Binding

Figure 5 shows *Binding* dimension breakdown. It can be seen that there is a "natural" binding for most tasks. For "Drag" and "Cursor" tasks, all gestures are world-dependent and require some information about the application environment features, because in the users' mental models, the location for these tasks is "naturally" defined with respect to world features.

For "*Select*" tasks, object-centric gestures are preferred by users because users think that location information is required for these tasks, and location is defined with respect to the object which is selected.

For the rest of tasks, gestures can occur anywhere, and hence, they are world-independent.

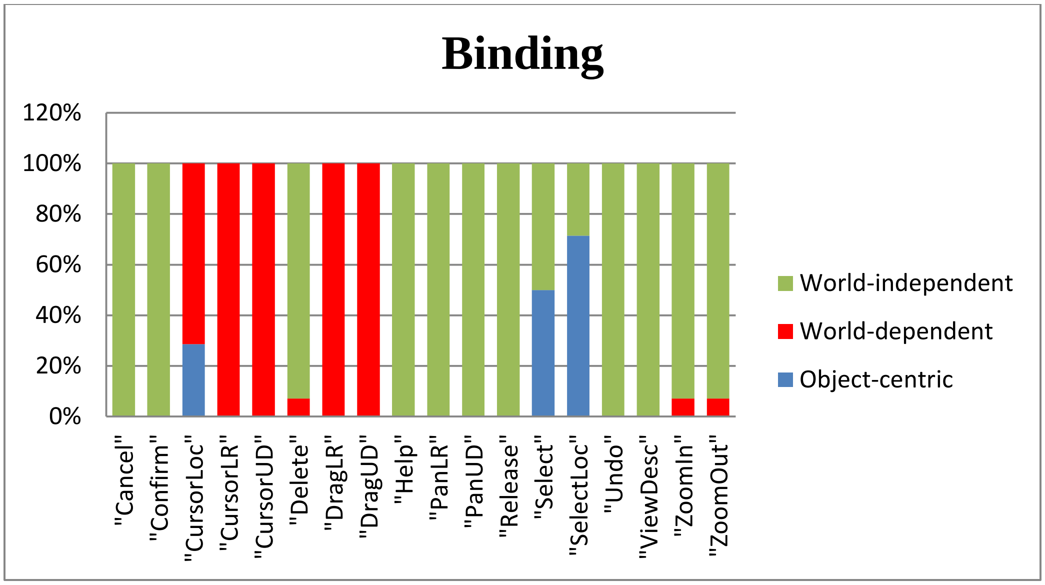


Figure 5. Binding Dimension Breakdown

4.1.5.4. Temporal

Figure 6 shows *Temporal* dimension breakdown. There is a "natural" relation between tasks and temporal dimension. Manipulative gestures performed to do "*Drag*" or "*Pan*", for example, are continuous as well. This is not the case for "*Zoom In/Out*" for which most gestures are abstract.

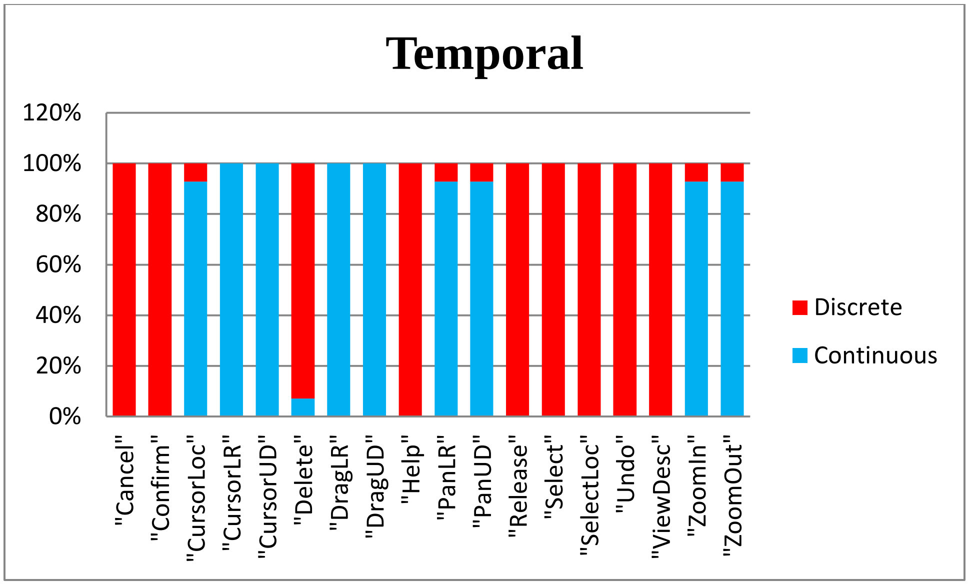


Figure 6. Temporal Dimension Breakdown

4.1.5.5. Context

Figure 7 shows Context dimension breakdown. As can be seen, overall, most gestures require no context while being performed.

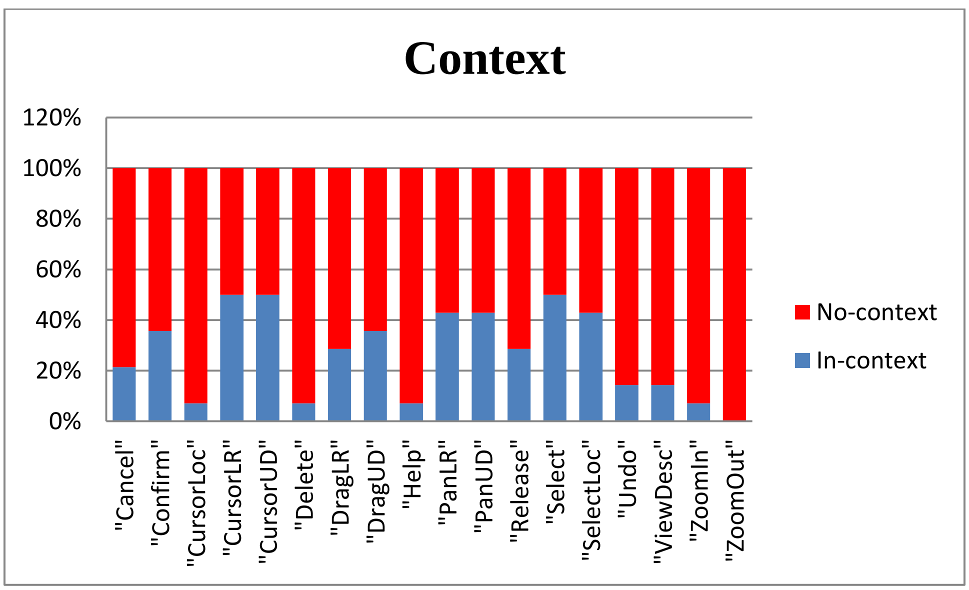


Figure 7. Context Dimension Breakdown

This implies the diversity among user-defined gestures that make most gestures correspond to one single task only. This is not the case for tasks which h performed by manipulative gestures though, including "*Drag*" and "*Pan*".

4.1.5.6. Dimensionality

Figure 8 shows the distribution of *Dimensionality* possible values for all 18 tasks.

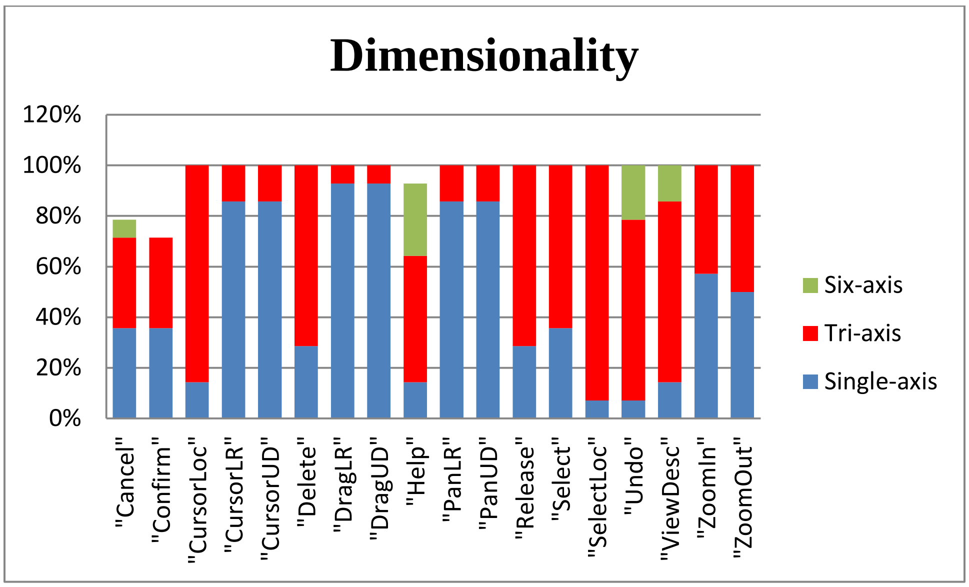


Figure 8. Dimensionality Breakdown

Double-axis gestures are absent in this chart because the experiment was conducted for mid-air gestures which are performed in 3D space. However, some gestures' motions occur in one direction only and involve one axis, *X*, *Y*, or *Z*. That's why some gestures are single-axis. For example, manipulative gestures performed to do "*Drag*" tasks, require users' arms to move in one direction/axis only, like left or right. Dimensionality is not applicable for static gestures, like symbolic gestures (showing thumb-up/down) for "*Cancel*" and "*Confirm*".

4.1.5.7. Complexity

Figure 9 shows *Complexity* dimension breakdown. As can be seen, most gestures are simple and can't be decomposed to two or more simple/atomic gestures.

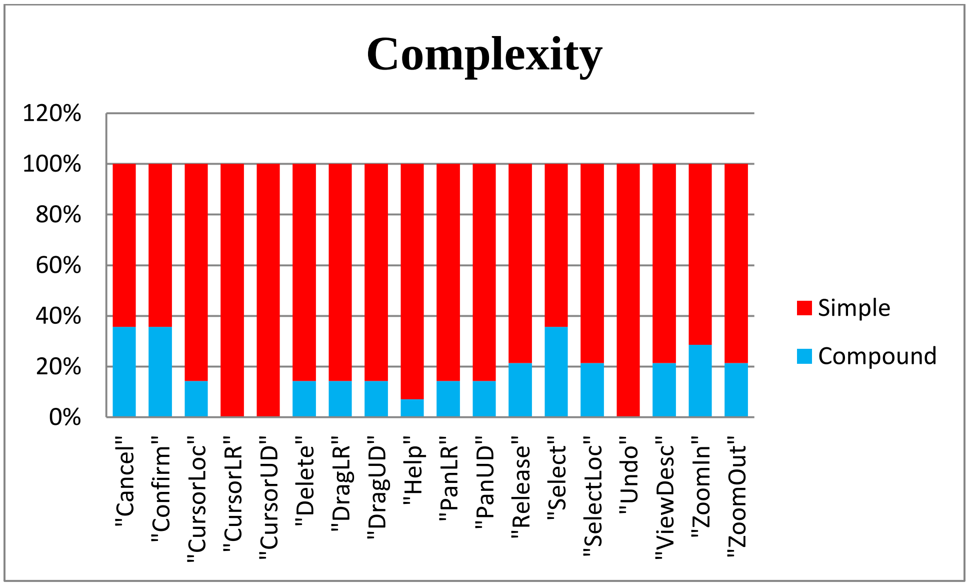


Figure 9. Complexity Dimension Breakdown

4.1.5.8. Body Part

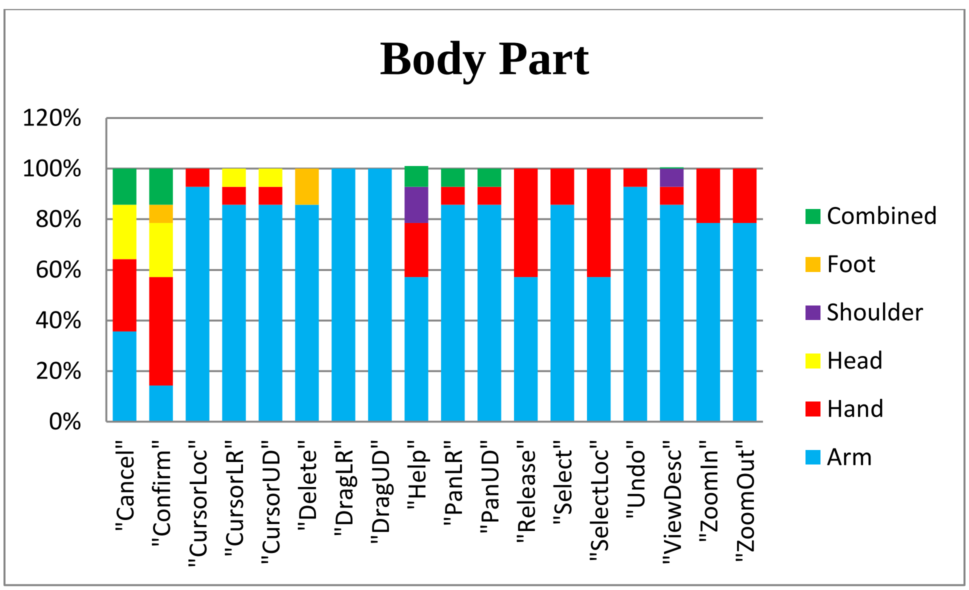


Figure 10. Body Part Dimension Breakdown

Figure 10 shows *Body Part* distribution for all tasks. It is remarkable that most gestures involve either arm or hand. Combined mid-air gestures, which involve more than one body part, are so rare in this experiment. It's mentioned that arm is by definition fixed in hand gestures.

4.1.5.9. Handedness

Figure 11 shows *Handedness* dimension breakdown for hand/arm gestures. It can be observed that the users mostly prefer to perform gestures by their dominant hand.

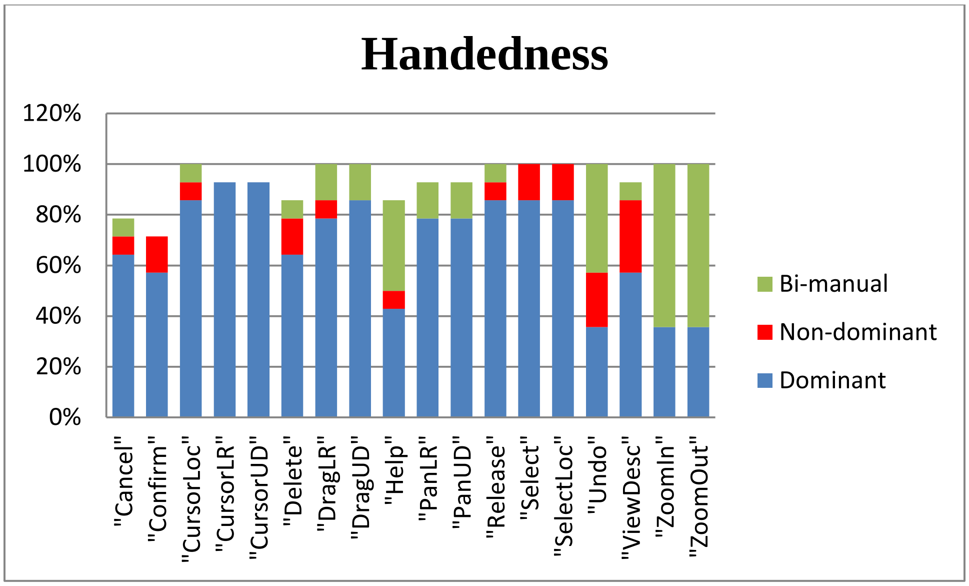


Figure 11. Handedness Dimension Breakdown

4.1.5.10. Hand Shape

Figure 12 shows the distribution of different hand shapes among gestures. This chart is drawn for most frequent hand shapes. Set of all common hand shapes have already been presented in Figure 2. *Index Finger* and *Flat Hand* are the most frequent hand shapes used to performed gestures. Specifically, using *Index Finger* hand shape is preferred by users to perform "*Cursor*" and "*Select*" tasks.

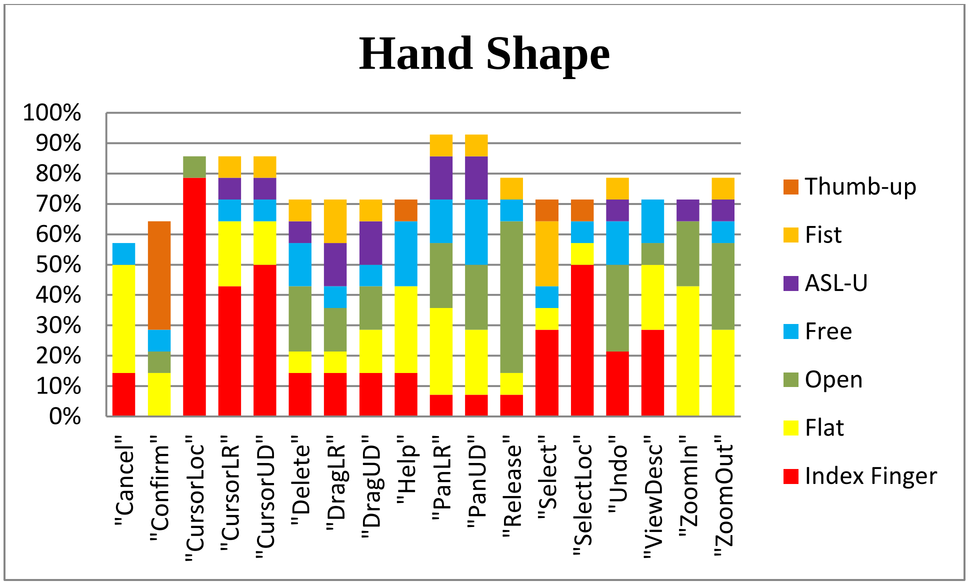


Figure 12. Hand Shape Dimension Breakdown

4.1.5.11. Range of Motion (ROM)

Figure 13 shows *Range of Motion (ROM)* breakdown for all 18 tasks. As mentioned in previous sections, *ROM* dimension has two values only, due to imprecision of observation and approximation method, which makes it hard to define and include "*Middle*" values.

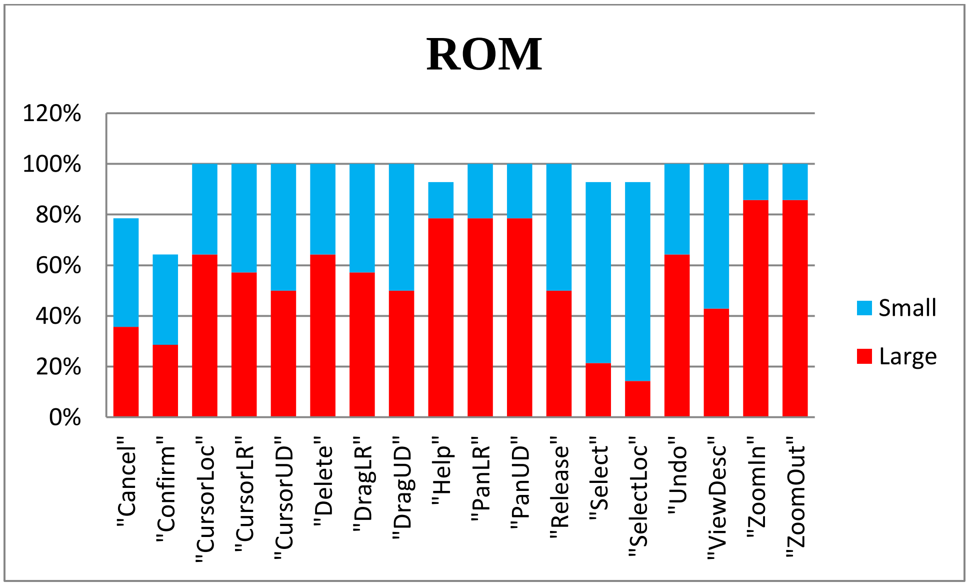


Figure 13. ROM Dimension Breakdown

4.2. Discussion

As can be seen in the breakdown charts (Figure 3 to Figure 13), the proposed taxonomy has distinguished the 756 mid-air gestures effectively. Overall, the gestures are distinct, thanks to the appropriate selection and definition of dimensions, and the distribution of values is well-balanced among the dimensions.

As for covering other types of gestures like motion gestures or surface gestures, there are dimensions in the taxonomy that can capture the specific features of these types, and hence, the taxonomy can cover the diversity in different application domains. For example, *Dimensionality* addresses the difference between surface gestures (*double-axis*) and mid-air gestures (*tri-axis* and *six-axis*). Also, other physical dimensions, especially *Hand Shape* and *ROM*, are able to classify gestures in all application domains.

Another significant observation in the results of the elicitation study is the impact of constraints/conditions on user's behavior, the process of designing and performing the gestures.

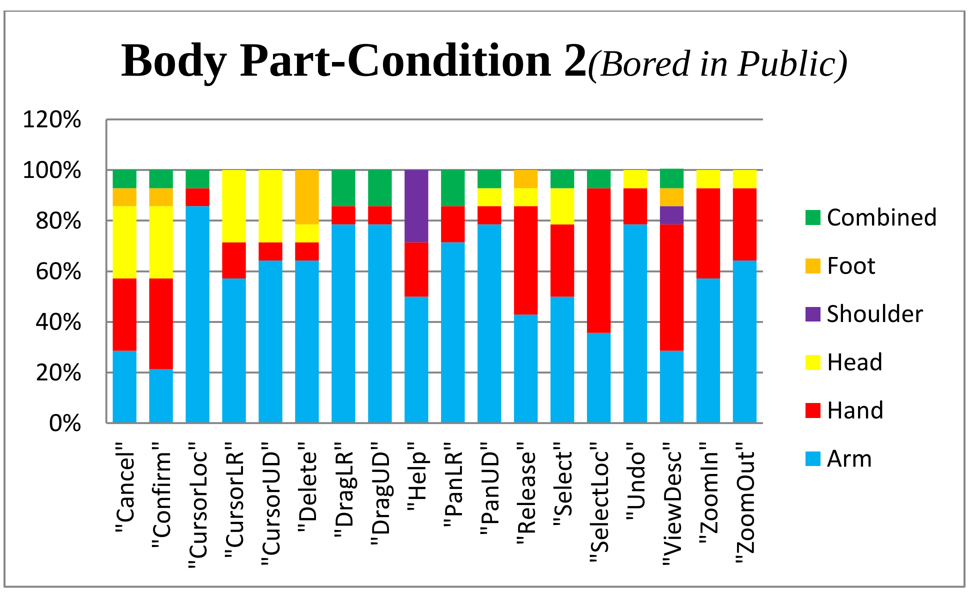


Figure 14. Body Part Breakdown under Condition 2

First, notice the impact of condition 2 on using body parts to perform the gestures.

Under condition 2, the participants were asked to pretend they were doing gestures while they were bored (weights wrapped on their wrists to help feeling bored), and in a public place where other people can see them interacting with the applications.

Figure 14 shows *Body Part* breakdown under condition 2. The decrease in using arm under condition 2 is considerable, and is depicted in Figure 15, whereas using hand gestures in which arm is fixed, and head gestures have increased.

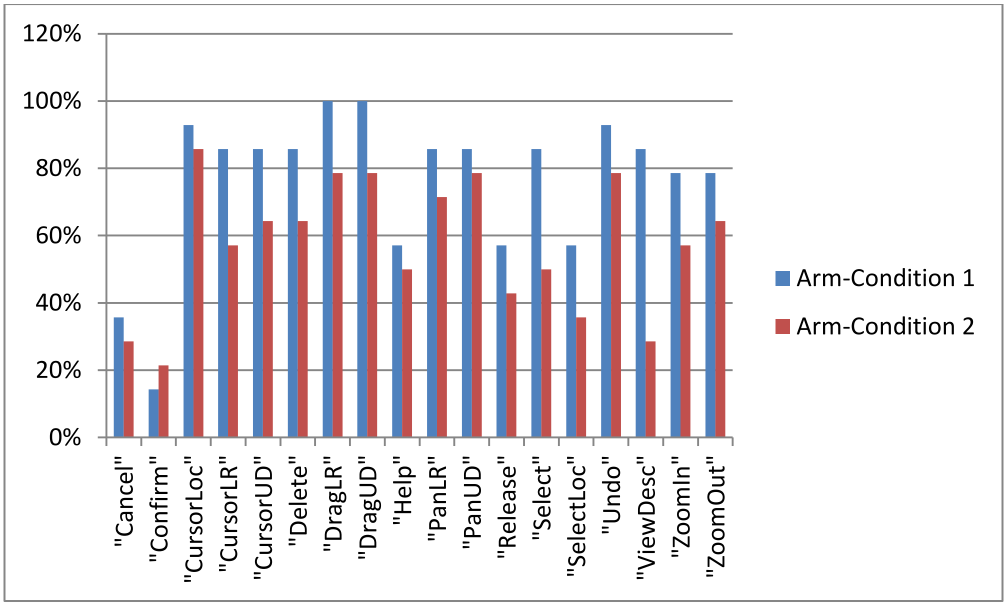


Figure 15. Arm Gestures' Decrease under Condition 2

Moreover, the impact of the constraints on ROM can be seen in Figure 16 and Figure 17. Under condition 1, most gestures have large ROM, whereas under condition 2, most gestures have small ROM.

This observation clearly implies that the proposed taxonomy not only is able to distinguish gestures well via appropriate dimensions, but also can capture the impact of constraints on designing and performing gestures.

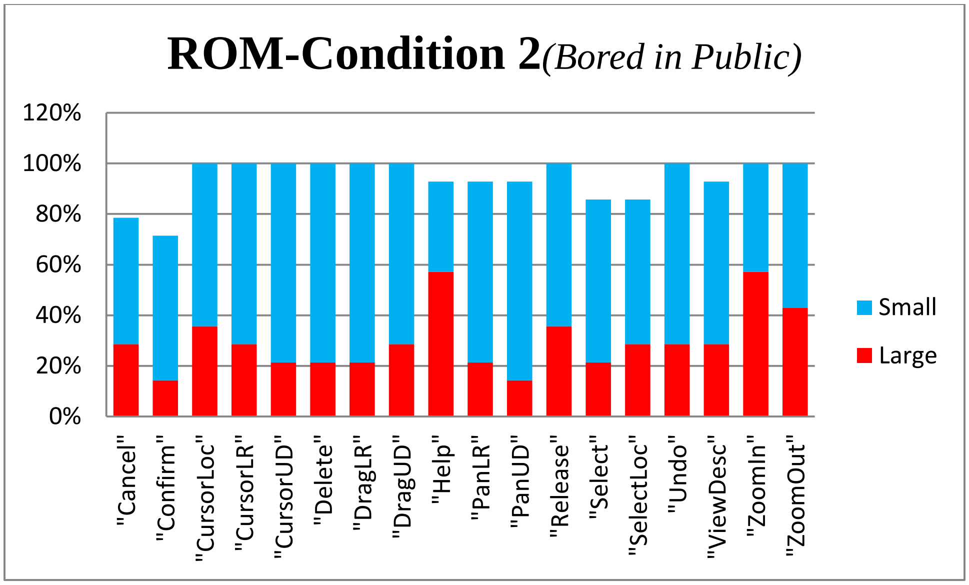


Figure 16. ROM Dimension Breakdown under Condition 2

Change from large to small ROM under condition 2 can be seen in Figure 17:

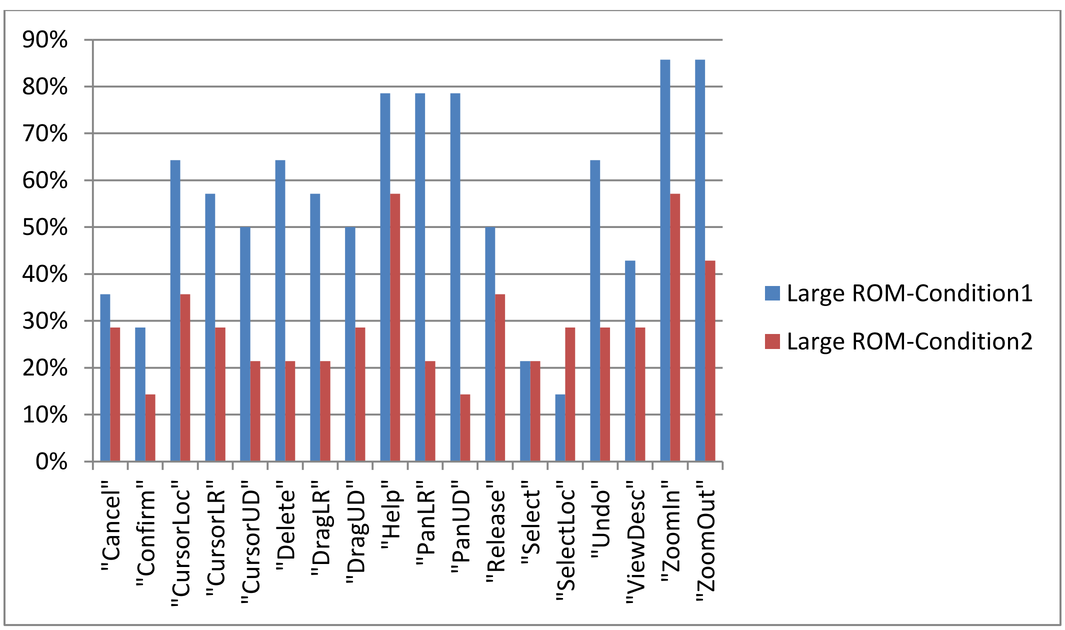


Figure 17. Large ROM's Decrease under Condition 2

5. SUMMARY AND CONCLUSIONS

The proposed taxonomy can help interactive system designers as well as HCI researchers to identify the design space and to be familiar with available possibilities, and potential issues in gesture design, particularly for mid-air gestures.

Given the existence of physical characteristics which are capable to elaborately address diverse and complex features of gestures in various application domains of HCI, the taxonomy can also benefit modern recognition projects and toolkits like *Microsoft Kinect* and *Leap Motion* project [2].

Some terms in earlier classifications, like *beats* as one of McNeill's four categories of gestures [3], are no longer capable, as a label in classification, to capture various features of gestures, or may refer to some unnecessary features (like rhythm of speech for *beat*), given the fact that life style of human being has changed a lot during past decades. Many interaction devices, like mouse, or touch pads, are now employed so commonly by users, and hence, people have different mental models to perform gestures. It's obviously more reasonable, for example, to replace *beat* term with *stroke*, because a *stroke* gesture is primarily intended to mimic tapping/clicking, and there is no rhythm involved with the user's mental model, as the definition of a *beat* gesture implies (see section 2.1.3). Thus, it is highly required to re-organize the terminology of gesture classification and update it as necessary, as to some extent I've done in this study.

As for future work, more elicitation studies for other types of gestures and areas of interactive systems' application domain like surface gestures and motion gestures is helpful to verify the performance of the proposed taxonomy, and to add, modify or remove the dimensions as necessary.

Finally, to verify the contribution of the proposed taxonomy in gesture recognition studies, it can be employed as a framework containing classes like *Hand Shape* and *ROM* to recognize and classify gestures in HCI. This would be the next chapter of my research.

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APPENDIX. SAMPLE SPREADSHEET OF CODED GESTURES

1	Participant	Condition	Task	Gesture Description	Nature	Form
2	P1	One	CursorLR	He moved his right hand to left, then to right.	manipulativ	dynamic
3	P1	One	CursorUD	He moved his right hand to up, and then down.	manipulativ	dynamic
4	P1	One	ViewDesc	He tapped his right hand two times quickly after each other.	pantomimic	stroke
5	P1	One	Select	He shaped his right hand as if he wants to pick sth.	pantomimic	dynamic
6	P1	One	DragLR	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
7	P1	One	DragUD	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
8	P1	One	Delete	He first picked the object, and then throw it away.	pantomimic	dynamic
9	P1	One	Release	He released his fingers that were bent to join together already.	pantomimic	dynamic
10	P1	One	Undo	He moved his left hand to up-left.	abstract	dynamic
11	P1	One	PanLR	He moved his right hand to left, then to right.	manipulativ	dynamic
12	P1	One	PanUD	He moved his right hand up, and then down.	manipulativ	dynamic
13	P1	One	ZoomIn	Using his both hands, while shaping them like ASL-F, he separated them from in to out.	abstract	dynamic
14	P1	One	ZoomOut	Exactly reversed form of ZoomIn.	abstract	dynamic
15	P1	One	CursorLoc	He moved his right index finger from position A, to B, and then to C.	manipulativ	dynamic
16	P1	One	SelectLoc	He picked the point while his hand was in ASL-Q shape.	pantomimic	dynamic
17	P1	One	Help	Shaping his right hand as thumb-up, he put it on the open/spread palm of his left hand.	symbolic	static
18	P1	One	Confirm	He shaped his right hand as tumb-up.	symbolic	static
19	P1	One	Cancel	He shaped his right hand as tumb-down.	symbolic	static
20	P1	TwoA	CursorLR	He moved his right hand to left, then to right.	manipulativ	dynamic
21	P1	TwoA	CursorUD	He moved his right hand to up, and then down.	manipulativ	dynamic
22	P1	TwoA	ViewDesc	He shaped his hand as if he wants to release sth, and like tapping, did it twice.	abstract	dynamic
23	P1	TwoA	Select	He shaped his right hand as if he wants to pick sth.	pantomimic	dynamic
24	P1	TwoA	DragLR	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
25	P1	TwoA	DragUD	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
26	P1	TwoA	Delete	He first picked the object with his right hand, and then throw it away.	pantomimic	dynamic
27	P1	TwoA	Release	He released his fingers that were bent to join together already while moving his right hand.	pantomimic	dynamic
28	P1	TwoA	Undo	He used his both hands hands and showed a release gesture.	abstract	dynamic
29	P1	TwoA	PanLR	He moved his right hand to left, and then right.	manipulativ	dynamic
30	P1	TwoA	PanUD	He moved his right hand up, and then down.	manipulativ	dynamic
31	P1	TwoA	ZoomIn	He put his fingers together, and then like picking, moved it towards himself.	abstract	dynamic
32	P1	TwoA	ZoomOut	Just reversed form of ZoomIn, the direction was towards the screen, and he opened his hand.	abstract	dynamic
33	P1	TwoA	CursorLoc	He moved his index finger from position A, to B, and then to C.	manipulativ	dynamic
34	P1	TwoA	SelectLoc	He picked the point while his hand was in ASL-Q shape.	abstract	dynamic
35	P1	TwoA	Help	Shaping his right hand as thumb-up, he put it on the open open palm of his left hand.	symbolic	static
36	P1	TwoA	Confirm	He showed a thumb-up.	symbolic	static
37	P1	TwoA	Cancel	He showed a thumb-down.	symbolic	static

38	P1	TwoB	CursorLR	He moved his right hand to left, then to right.	manipulativ	dynamic
39	P1	TwoB	CursorUD	He moved his right hand to up, and then down.	manipulativ	dynamic
40	P1	TwoB	ViewDesc	He tapped his right hand two times quickly after each other.	abstract	stroke
41	P1	TwoB	Select	He shaped his right hand as if he wants to pick sth.	pantomimic	dynamic
42	P1	TwoB	DragLR	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
43	P1	TwoB	DragUD	He first selected by shaping his hand similar to Select(picking), and then moved his hand.	manipulativ	dynamic
44	P1	TwoB	Delete	He first picked the object, and then throw it away.	pantomimic	dynamic
45	P1	TwoB	Release	He tapped his right hand two times quickly after each other.	abstract	stroke
46	P1	TwoB	Undo	While moving his both hands forward, he opened his hands.	abstract	dynamic
47	P1	TwoB	PanLR	He moved his right hand to left, and then right.	manipulativ	dynamic
48	P1	TwoB	PanUD	He moved his right hand up, and then down.	manipulativ	dynamic
49	P1	TwoB	ZoomIn	He shaped his hand like ASL-Q, and then like picking, moved it towards himself.	abstract	dynamic
50	P1	TwoB	ZoomOut	Just reversed form of ZoomIn, the direction was towards the screen, and he opened his hand.	abstract	dynamic
51	P1	TwoB	CursorLoc	He moved his index finger from position A, to B, and then to C.	manipulativ	dynamic
52	P1	TwoB	SelectLoc	He picked the point while his hand was in ASL-Q shape.	pantomimic	dynamic
53	P1	TwoB	Help	Shaping his right hand as thumb-up, he put it on the open spread palm of his left hand.	symbolic	static
54	P1	TwoB	Confirm	He showed a thumb-up.	symbolic	static
55	P1	TwoB	Cancel	He showed a thumb-down.	symbolic	static

1	Participant	Condition	Task	Binding	Temporal	Context	Dimension	Complexity	Body Part	Handedness	Hand Shape	ROM
2	P1	One	CursorLR	world-dependent	continuous	in	single	simple	arm	dominant	flat	large
3	P1	One	CursorUD	world-dependent	continuous	in	single	simple	arm	dominant	flat	large
4	P1	One	ViewDesc	world-independent	discrete	no	tri	compound	arm	dominant	flat	small
5	P1	One	Select	world-independent	discrete	in	tri	simple	arm	dominant	Joined Finge	small
6	P1	One	DragLR	world-dependent	continuous	no	single	compound	arm	dominant	Joined Finge	large
7	P1	One	DragUD	world-dependent	continuous	no	single	compound	arm	dominant	Joined Finge	large
8	P1	One	Delete	world-independent	discrete	no	tri	compound	arm	dominant	Joined Finge	large
9	P1	One	Release	world-independent	discrete	in	tri	simple	arm	dominant	open	small
10	P1	One	Undo	world-independent	discrete	no	tri	simple	arm	non-domina	open	large
11	P1	One	PanLR	world-independent	continuous	in	single	simple	arm	dominant	flat	large
12	P1	One	PanUD	world-independent	continuous	in	single	simple	arm	dominant	flat	large
13	P1	One	ZoomIn	world-independent	continuous	no	single	simple	arm	bi-manual	ASL-F	large
14	P1	One	ZoomOut	world-independent	continuous	no	single	simple	arm	bi-manual	ASL-F	large
15	P1	One	CursorLoc	world-dependent	continuous	no	tri	simple	arm	dominant	Index Finge	large
16	P1	One	SelectLoc	world-independent	discrete	no	tri	simple	arm	dominant	ASL-Q	small
17	P1	One	Help	world-independent	discrete	no	N/A	simple	hand	bi-manual	thumb-up	N/A
18	P1	One	Confirm	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-up	N/A
19	P1	One	Cancel	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-dow	N/A
20	P1	TwoA	CursorLR	world-dependent	continuous	in	single	simple	arm	dominant	flat	small
21	P1	TwoA	CursorUD	world-dependent	continuous	in	single	simple	arm	dominant	flat	small
22	P1	TwoA	ViewDesc	world-independent	discrete	no	tri	compound	hand	dominant	free	small
23	P1	TwoA	Select	world-independent	discrete	in	tri	simple	arm	dominant	Joined Finge	small
24	P1	TwoA	DragLR	world-dependent	continuous	no	single	compound	arm	dominant	Joined Finge	small
25	P1	TwoA	DragUD	world-dependent	continuous	no	single	compound	arm	dominant	Joined Finge	large
26	P1	TwoA	Delete	world-independent	discrete	no	tri	compound	arm	dominant	Joined Finge	small
27	P1	TwoA	Release	world-independent	discrete	in	tri	compound	arm	dominant	open	small
28	P1	TwoA	Undo	world-independent	discrete	in	tri	simple	arm	bi-manual	open	small
29	P1	TwoA	PanLR	world-independent	continuous	in	single	simple	arm	dominant	flat	small
30	P1	TwoA	PanUD	world-independent	continuous	in	single	simple	arm	dominant	flat	small
31	P1	TwoA	ZoomIn	world-independent	continuous	in	tri	simple	arm	dominant	Joined Finge	large
32	P1	TwoA	ZoomOut	world-independent	continuous	in	tri	simple	arm	dominant	open	small
33	P1	TwoA	CursorLoc	world-dependent	continuous	no	tri	simple	arm	dominant	Index Finge	large
34	P1	TwoA	SelectLoc	world-independent	discrete	in	tri	simple	hand	dominant	ASL-Q	small
35	P1	TwoA	Help	world-independent	discrete	no	N/A	simple	hand	bi-manual	thumb-up	N/A
36	P1	TwoA	Confirm	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-up	N/A
37	P1	TwoA	Cancel	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-dow	N/A

38	P1	TwoB	CursorLR	world-dependent	continuous	in	tri	simple	arm	dominant	flat	small
39	P1	TwoB	CursorUD	world-dependent	continuous	in	tri	simple	arm	dominant	flat	large
40	P1	TwoB	ViewDesc	world-independent	discrete	no	tri	compound	hand	dominant	flat	small
41	P1	TwoB	Select	world-independent	discrete	in	tri	simple	arm	dominant	Joined Finge	large
42	P1	TwoB	DragLR	world-dependent	continuous	no	tri	compound	arm	dominant	Joined Finge	large
43	P1	TwoB	DragUD	world-dependent	continuous	no	tri	compound	arm	dominant	Joined Finge	large
44	P1	TwoB	Delete	world-independent	discrete	no	tri	compound	arm	dominant	Joined Finge	large
45	P1	TwoB	Release	world-independent	discrete	in	tri	compound	hand	dominant	flat	small
46	P1	TwoB	Undo	world-independent	discrete	no	tri	simple	arm	bi-manual	open	small
47	P1	TwoB	PanLR	world-independent	continuous	in	single	simple	arm	dominant	flat	small
48	P1	TwoB	PanUD	world-independent	continuous	in	single	simple	arm	dominant	flat	small
49	P1	TwoB	ZoomIn	world-independent	continuous	in	tri	simple	arm	dominant	ASL-Q	small
50	P1	TwoB	ZoomOut	world-independent	continuous	no	tri	simple	arm	dominant	ASL-L	small
51	P1	TwoB	CursorLoc	world-dependent	continuous	no	tri	compound	arm	dominant	Index Finge	large
52	P1	TwoB	SelectLoc	world-independent	discrete	no	tri	simple	arm	dominant	ASL-Q	small
53	P1	TwoB	Help	world-independent	discrete	no	N/A	simple	hand	bi-manual	thumb-up	N/A
54	P1	TwoB	Confirm	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-up	N/A
55	P1	TwoB	Cancel	world-independent	discrete	no	N/A	simple	hand	dominant	thumb-dow	N/A