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Motor-Intuitive Interactions Based on Image Schemas: Aligning Touchless Interaction Primitives with Human Sensorimotor Abilities

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Elicitation and evaluation studies investigated intuitiveness of touchless gestures but did not operationalize intuitiveness. For example, studies found that users fail to make accurate 3D strokes as interaction commands. But this phenomenon remains unexplained. In this paper, we first explain how making accurate 3D strokes is generally unintuitive, because it exceeds our sensorimotor knowledge. We then introduce motor-intuitive, touchless interaction that uses sensorimotor knowledge by relying on image schemas. Specifically, we propose an interaction primitive—mid-air, directional strokes—based on space schemas up–down and left–right. In a controlled study with large displays, we found that biomechanical factors affected directional strokes. Strokes were efficient (0.2 s) and effective (12.5° angular error), but affected by directions and length. Our work operationalized intuitive touchless interaction using the continuum of knowledge in intuitive interaction, and demonstrated how user performance of a motor-intuitive, touchless primitive based on sensorimotor knowledge (image schemas) is affected by biomechanical factors.

RESEARCH HIGHLIGHTS

- We operationalized touchless interaction using the continuum of knowledge.
- Users fail to make accurate 3D strokes, because it is an expertise level of knowledge.
- Motor-intuitive interactions based on image schemas use sensorimotor knowledge.
- We studied a motor-intuitive, touchless primitive: mid-air directional strokes.
- Results found mid-air strokes efficient (0.2 s) and effective (12.5° angular error).
- Biomechanical factors affected the user performance of mid-air strokes.

Keywords: gestural input; empirical studies in HCI; interaction design theory, concepts and paradigms; intuitive interaction; large display interaction; natural user interfaces

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1. INTRODUCTION

The emergence of natural user interfaces (NUI) has spurred interest in critically examining the concept of *natural* or *intuitive*. This inquiry is crucial because emerging forms of NUIs, such as touchless interfaces are becoming increasingly relevant for interacting with large displays in a variety of contexts: in the absence of interaction devices (e.g. in public places), in sterile environments (e.g. in surgery rooms) or during sporadic browsing of multimedia information (e.g. in interactive TVs). Although in some of these scenarios users can use handheld devices, such as smartphones or tablets, touchless gestures relieve users from the burden of interacting with an additional medium between the user and the system (Morris, 2012; O'Hara *et al.*, 2013). However, while the industry is rushing to market new touchless products (e.g. the Samsung® Smart TV), the complexity emerging from the increased sophistication of such devices and our abilities to interact with them intuitively remains largely unexplored.

To explore *intuitiveness* (or naturalness) in touchless interactions, researchers mostly follow either of these two approaches: gesture elicitation (e.g. Aigner *et al.*, 2012, Vatavu and Zaiti, 2014) or gesture evaluation (e.g. Ren and O'Neill, 2012). For example, a gesture elicitation study reported that users would prefer a 'wiping' hand movement over a static hand sign to trigger a 'delete' action (Grandhi *et al.*, 2011). In a gesture evaluation study, researchers found that users evaluated 'dwelling' as the most intuitive gesture to select a target (Hespanhol *et al.*, 2012). Neither of these existing approaches to investigate intuitiveness of touchless interactions operationalizes the concept of intuitiveness. Therefore, we often encounter observations from evaluation studies about user limitations or failure of certain gestures without any proper explanation. For example, a common touchless interaction primitive to indicate 'selection' uses dynamic gestures, where meaning is assigned to particular translations (i.e. hand movements) in space. Recent works examining this interaction primitive (Guimbretière and Nguyen, 2012; Ren and O'Neill, 2012) report users' limitations in *making precise hand trajectories in 3D space.* Despite repeated observations of this phenomenon, we still lack a causal explanation.

We argue that to explain the potential and limitations of current touchless primitives, we need to consider the level of knowledge that is being used in such interaction contexts. The level of knowledge at play while interacting with computers is classified into a *continuum of knowledge* by the intuitive interaction framework (Blackler and Hurtienne, 2007). In this continuum, the level of intuitiveness of the interaction grammar is inversely proportional to the artificiality of the knowledge that a user relies on to interact with. Intuitive interaction is thus characterized as the extent to which users' unconscious application of prior knowledge leads to effective interaction (Hurtienne and Israel, 2007). In the case of touchless interactions, designers often treat human abilities as a 'black box', assuming that our ability to interact with the physical world *directly translates* into our ability to perform exact gestures in space. Yet, intuitive interaction does not work in this way. To unleash intuitive user experiences, designers need to examine the relationship between a given level of knowledge and the corresponding interaction primitives that align well with that knowledge.

The main contribution of this paper is to introduce the concept of motor-intuitive, touchless interactions. Specifically, we propose and evaluate a novel, motor-intuitive, touchless interaction primitive—mid-air, directional strokes—based on space schemas: *up–down* and *left–right.* To investigate how other factors, such as biomechanical properties of the human body, affect performance of our proposed motor-intuitive touchless primitive, we conducted a controlled experiment. As per the intuitive interaction framework, motor-intuitive interactions have the potential to establish a new touchless interaction grammar that is based on what users are able to accomplish without further cultural or advanced expertise. Our work makes the following contributions:

1. We provide a theoretical explanation of human limitations in making accurate 3D trajectories (Section 3) by drawing an analogy between 'reaching for an object' and freehand gesturing towards a display. This explanation is based on the consideration of the sensorimotor level in the continuum of knowledge that is at play during such interactions. We further discuss how lack of feedback in touchless interactions can also explain such motor limitations.
2. We introduce *motor-intuitive*, touchless interactions based on image schemas. Specifically we propose a touchless interaction primitive that draws on the sensorimotor level of knowledge—the two space schemas, *up–down* and *left–right* (Section 4).
3. Finally, we investigate how biomechanical factors affect user performance of our proposed interaction primitive. Grounded in our empirical results, we provide practical design guidelines for intuitive touchless interactions and large-display touchless interactions (Section 7.2). These include pointers on designing dynamic touchless gestures, characterization of right-handed users' control space based on user performance and implications towards designing UI elements for large displays (e.g. touchless menus).

Our work is a first step towards applying the continuum of knowledge in intuitive interaction to define touchless interaction primitives. Our findings can inform fundamental design decisions to align touchless user interfaces with human sensorimotor abilities, thus making them intuitive to use.

2. RELATED WORK

While designing gesture primitives for touchless interfaces—often referred as a kind of NUI—existing studies associate the same meaning with 'natural' and 'intuitive' (Aigner *et al.*, 2012; Grandhi *et al.*, 2011; Hespanhol *et al.*, 2012; Lee, 2010; Morris, 2012; O'Hara *et al.*, 2013; Vatavu and Zaiti, 2014; Wigdor and Wixon, 2011). The meaning of 'natural' or 'intuitive' (we use these terms interchangeably in this paper) that is adopted by these studies does not go beyond the vernacular definition of *instinctive* or *spontaneous*. Our work is an attempt to operationalize 'intuitive' in touchless interactions, and builds upon the crossroads of two research areas: intuitive interaction and NUIs.

2.1. Intuitive interaction

The intuitive interaction framework defines intuitive interaction (or intuitivity) as the extent to which users' unconscious application of prior knowledge leads to effective interaction (Blackler and Hurtienne, 2007). While a similar framework, reality-based interaction (Jacob *et al.*, 2008), identifies core themes (such as naïve physics or body awareness and skills) to *scope* what can be called real (or natural), intuitive interaction framework provides a continuum of knowledge to *classify* intuitivity (Hurtienne and Israel, 2007). This bottom-up continuum of knowledge classifies intuitive interaction according to four different levels of prior knowledge: innate, sensorimotor, culture and expertise. According to this continuum, the higher an interface requires specialization of knowledge the lower is the expected speed of knowledge retrieval, and hence less intuitive to use. Although this continuum of knowledge has been used to propose tangible interaction primitives (Hurtienne and Israel, 2007), the use of this continuum in touchless interaction remains largely unexplored. According to this continuum of knowledge, touchless primitives drawing upon the sensorimotor level of knowledge would be far more intuitive to use than primitives based on the expertise level.

2.2. Natural user interface

Many ongoing debates stem from the term *natural* in NUIs (Norman, 2010; O'Hara *et al.*, 2013; Wigdor and Wixon, 2011). NUIs promise to offer an intuitive interface modality, one that does not require users to develop special skills for communicating with computers, but allows users to use their natural abilities. But what is natural (or intuitive or like real-world) for users? Norman (2010) discussed that the notion of naturalness in a user interface is not an axiomatic truth, but achieved through sufficient feedback, effective feedforward and perceived affordances. O'Hara *et al.* (2013) discuss how naturalness of an interaction modality, such as touchless, is derived from the actions it enables in different communities of practice and settings (the interactional perspective). According to Wigdor and Wixon (2011, p. 9), natural is a design philosophy that enables an iterative product-creation process, rather than a mimicry of the real world. Overall, there is an urgent need to understand what is natural for users, and then leverage it towards building NUIs.

In touchless interaction, elicitation and evaluation studies on hand gestures continue to inform the naturalness of interaction primitives. For example, empirical studies have shown that unguided mid-air gestures—especially circular in design—are generally less efficient and more fatiguing than linear gestures (Nancel *et al.*, 2011). Grandhi *et al.* (2011) reported user preference towards bimanual gestures, and intuitiveness of dynamic gestures (iconic representation of the motion required for the manipulation) over static iconic hand poses. Different kinds of hand gestures have also been evaluated as command selection techniques, such as push (Hespanhol *et al.*, 2012), grab, finger-count (Bailly *et al.*, 2011), mark (Guimbretière and Nguyen, 2012; Ren and O'Neill, 2012) or roll-and-pinch (Ni *et al.*, 2008). While these studies report certain gestures to be intuitive compared with others, they do not classify their intuitivity or provide an explanation about why other gestures failed to be intuitive. We argue that the continuum of knowledge in intuitive interaction can operationalize the intuitiveness of touchless interfaces by informing the design of touchless interaction primitives, which are the building blocks of any interaction language (Wigdor and Wixon, 2011, p. 116).

3. TOUCHLESS INTERACTION PRIMITIVES AND OUR LIMITATION TO PERFORM ACCURATE 3D TRAJECTORIES

Human gesturing has been used in different application domains of HCI for over 50 years. In 2005, Karam and Schraefel provided a high-level classification of human gestures according to gesture styles, input technologies, output technologies and application domains. Since 2010, with recent advancements in markerless tracking, mid-air gestures are being increasingly used as interaction primitives in touchless interaction. To classify the physical mechanics of these gestures, we build upon the taxonomy proposed by Vatavu and Pentiuc (2008) (Fig. 1). Vatavu and Pentiuc classified hand gestures into four categories: static simple, static generalized, dynamic simple and dynamic generalized gestures. Static simple gestures are gestures that only involve the use of a single posture over a certain period of time (e.g. a closed hand, Bailly *et al.*, 2011). Static generalized gestures are gestures that involve a series of consecutive postures over certain periods of time (e.g. rolling the wrist and pinching, Ni *et al.*, 2008; or finger movements, Vogel and Balakrishnan, 2005). Dynamic simple gestures are gestures that use information about the underlying motion trajectory but not the posture information (e.g. drawing shapes or characters in mid-air, Gustafson *et al.*, 2010; or performing accurate 3D strokes to invoke commands in a 3D marking menu, Ren and O'Neill, 2012). Dynamic generalized gestures are gestures that use the information about both the motion trajectory and the posture (e.g. select by moving an open palm *normal* to the display, Hespanhol *et al.*, 2012; or pinch and 3D stroke, Guimbretière and Nguyen, 2012). Each of these four categories of gestures is defined as a function of time. Hence, we call this a temporal classification.

Mid-air gestures as interaction primitives can also be classified from a spatial perspective—describing the relationship between the position of the gesture in the input space and the UI elements in the display space. Spatially, a gesture can be referential or non-referential. Referential gestures are gestures that use the spatial information along with posture and/or motion trajectory. For example, to select an icon with a *reach* gesture users need to move across the icon's boundary (Ren and O'Neill, 2012); or to select using a *dwell* gesture users need to point to an object and hold their open palm (Hespanhol

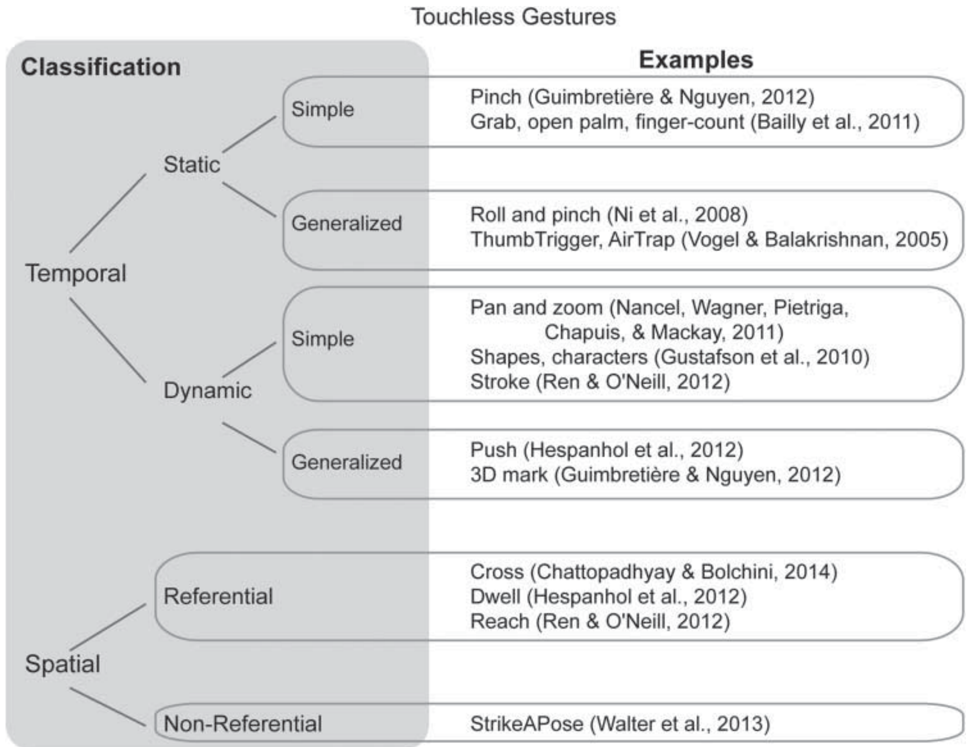

Figure 1. We present a taxonomy to classify the physical mechanics of device-free, mid-air gestures. We generalize the taxonomy proposed by Vatavu and Pentiuc (2008) as temporal, and further provide a spatial classification.

et al., 2012). Non-referential gestures are gestures that do not use any spatial information but only the posture and/or motion trajectory (e.g. touching the hip in StrikeAPose, Walter *et al.*, 2013).

Touchless interaction is limited by the absence of haptic feedback, and the decoupling between the display space (containing the goal of the interaction) and the input space (containing the motor action) (O'Hara *et al.*, 2013). Specifically, dynamic touchless gestures (simple or generalized) suffer from human limitations to make accurate three-dimensional movements in mid-air (such as making accurate 3D strokes, or constraining hand movements in a 2D plane). Previous research that evaluated touchless gestures has reported this phenomenon (Bailly *et al.*, 2011; Guimbretière and Nguyen, 2012; Hespanhol *et al.*, 2012; Ren and O'Neill, 2012). Guimbretière and Nguyen (2012) report the unreliability of a three-dimensional marking menu, because users failed to gauge a 3D angle for the *mark* gesture. Ren and O'Neill (2012) report similar findings for their *stroke* technique. For *push-to-select* gesture, Hespanhol *et al.* (2012) report a translation-action ambiguity problem. A touchless gesture suffers from translation-action ambiguity, when users frequently trigger actions while repositioning their body in space (Fig. 2). Although the literature widely reports human limitations to make precise 3D trajectories, we still lack a causal explanation.

We explain human limitations in making accurate 3D trajectories by drawing an analogy between 'reaching for an object' (a sensorimotor level of knowledge) and freehand gesturing towards a display. In daily life, we mostly move our hands in an unconstrained, three-dimensional space. To reach for an object, among infinitely many trajectories, we choose the one that minimizes our metabolic energy costs (Alexander, 1997). Hence, we are not familiar with planning movements that force us to calculate accurate 3D trajectories, or follow a combination of orthogonal paths. Based on this minimum energy cost model, we argue that users fail to perform accurate 3D strokes in mid-air as they cannot leverage their familiar mental model of movement planning. Since making accurate 3D strokes exceeds our sensorimotor level of knowledge, according to the continuum of knowledge in intuitive interaction, this would be classified as an expertise level of knowledge (Hurtienne and Israel, 2007).

Furthermore, the lack of accuracy in making 3D trajectories can be explained by the limited feedback in touchless interactions. To perform touchless interactions we rely solely on visual feedback and proprioception (our sense of position and orientation of the body, Mine *et al.*, 1997) because current touchless systems provide only visual cues on the display and no haptic feedback. Visual feedback—provided on a two-dimensional display—and proprioception cannot

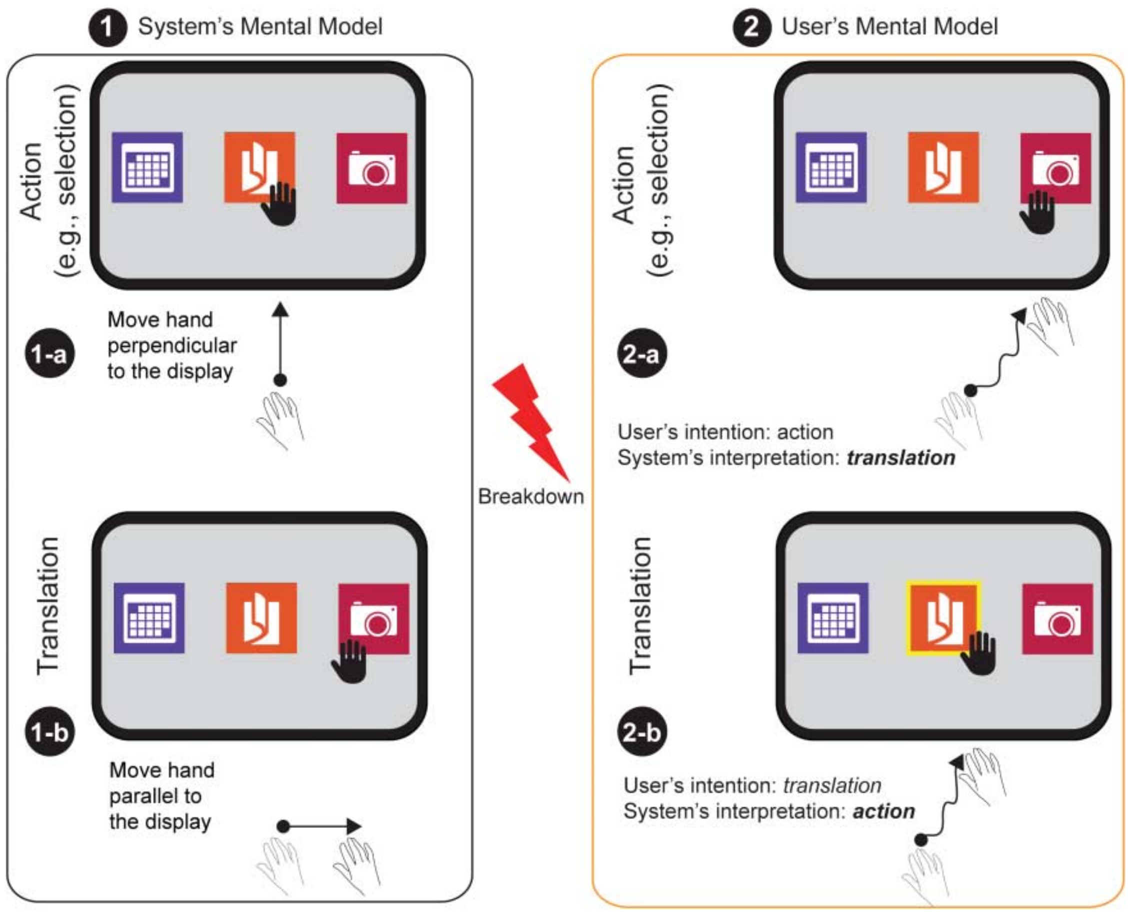

Figure 2. Some of the current technological systems (1) expect users to discriminate between action-gestures (1-a) and translation-gestures (1-b) by making orthogonal hand-movements. However, in daily life, we are continually moving our hands in an unconstrained, three-dimensional space. This tension between our familiar movements (2-a, 2-b) and technological expectations (1-a, 1-b) poses a *translation-action ambiguity* in touchless interactions.

sufficiently guide users to make accurate 3D trajectories. Whether manipulating visual feedback (e.g. laser rays in mid-air, or 3D visualization) or adding tactile feedback (e.g. airwave, Gupta *et al.*, 2013) can assist users to make accurate 3D trajectories is yet to be explored.

4. MOTOR-INTUITIVE INTERACTIONS: DESIGNING TOUCHLESS PRIMITIVES BASED ON IMAGE SCHEMAS

Our explanation for the lack of accuracy in making 3D trajectories was based on the sensorimotor level of knowledge in the continuum of intuitive interaction: users fail to make 3D trajectories because they cannot apply their prior knowledge that they learned while interacting with the physical world. Hence, we argue that the potential and limitations of touchless primitives can be explained using the continuum of knowledge in intuitive interaction (Hurtienne and Israel, 2007). To illustrate our argument, we introduce motor-intuitive, touchless interactions based on image schemas that draw on our sensorimotor level of knowledge.

4.1. Motor-intuitive touchless interactions

Motor-intuitive touchless interactions are interactions where users are able to apply their pre-existing sensorimotor knowledge unconsciously. Specifically, they do not need to learn new motor planning or execution skills. Since childhood, we perform basic motor movements, such as pushing, pulling, grasping or moving up and down. These motor intuitions are closely related to image schemas, such as *up–down*, *near–far* or *left–right*. Image schemas are a schematic representation of our daily sensorimotor experiences—an abstraction of the different patterns by which our body interacts with the physical world (Johnson, 1987; Lakoff and Johnson, 1980). Hurtienne and Israel (2007) classified image schemas in eight different groups: basic, space, containment, identity, multiplicity, process, force and attribute (Table 1, p. 130, Hurtienne and Israel, 2007). Motor-intuitive interaction primitives are based on space

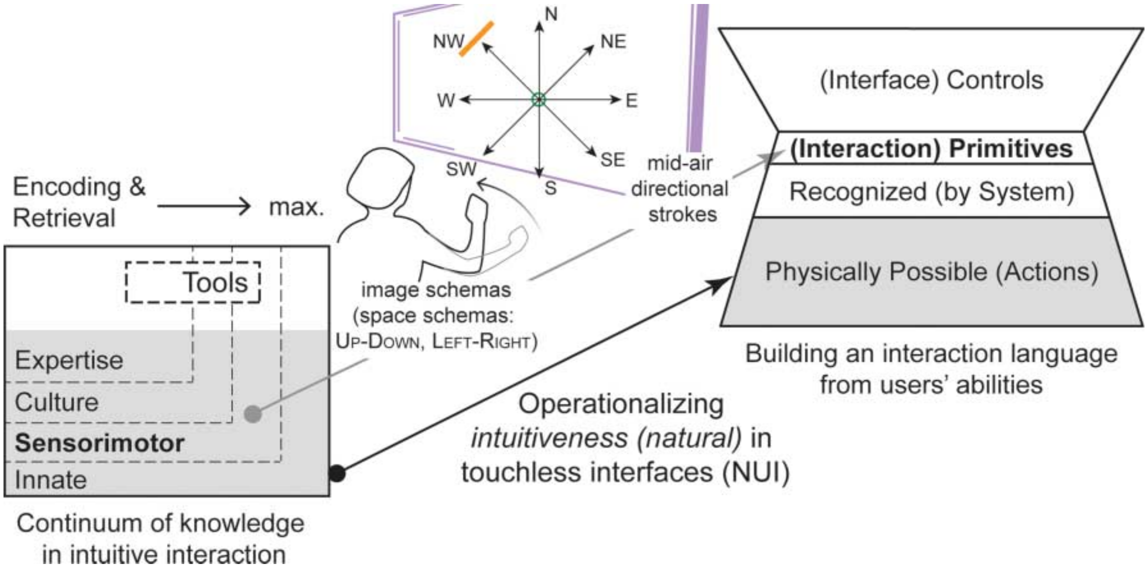

Figure 3. We argue that the continuum of knowledge in intuitive interaction (left, Hurtienne and Israel, 2007 © 2007 ACM, reprinted with permission) can classify mid-air gestures into different levels of intuitiveness, and thereby operationalize the intuitiveness of touchless interfaces (right, Wigdor and Wixon, 2011, p. 116 © 2011 Elsevier, reprinted with permission). Our work illustrates this argument by designing and evaluating a touchless interaction primitive (mid-air, directional strokes) that draws on our sensorimotor level of knowledge (image schemas, more specifically the *up–down* and the *left–right* space schema). To evaluate our proposed interaction primitive, we investigated user performance when making directional strokes in eight compass directions.

schemas: schemas that represent our everyday motor-actions in navigating 3D space such as up–down, left–right, near–far, front–back, center–periphery, straight–curved, contact, path, scale or location. Intuitiveness of a motor-intuitive interaction cannot be determined solely by its performance measures (efficiency and effectiveness), but depends on the level of knowledge at play during the interaction. With practice, users may perform certain motor actions accurately (expertise level), but motor-intuitive interactions are based on image schemas that act beyond our conscious awareness (sensorimotor level). Hence, motor-intuitive interactions would be easy-to-perform, learn and remember.

Because motor-intuitive interactions are based on image schemas that act beyond our conscious awareness, they are unlikely to be self-reported in traditional gesture elicitation studies. Gesture elicitation studies aim at gathering gesture primitives as suggestions from end users for any particular interaction (e.g. moving hand upward to increase the volume of a TV, Vatavu and Zaiti, 2014). As expected, participants of these studies use their previous knowledge and acquired skills to suggest touchless interaction primitives. They certainly use metaphors to map the gestures to their meaning (Lakoff and Johnson, 1980), such as the motion of cutting with an imaginary knife to mean a *slice* gesture (Grandhi *et al.*, 2011). However, with respect to the continuum of knowledge (Fig. 3, left), these metaphors mostly reside at the levels of tool, expertise or culture. Thus, it is not surprising that researchers report limitations of elicitation studies due to expertise bias (previously acquired gesture interaction models, such as mouse, Morris *et al.*, 2014; Vatavu and Zaiti, 2014) or cultural bias. As an alternative to gesture elicitation, in our approach towards designing intuitive touchless interaction primitives, we shifted to the sensorimotor level of the continuum of knowledge and introduced motor-intuitive, touchless interactions. To exemplify our concept, we propose a novel, motor-intuitive, touchless primitive: mid-air directional strokes.

4.2. Mid-air directional strokes: a motor-intuitive touchless primitive based on image schemas

We propose a motor-intuitive, touchless interaction primitive: mid-air strokes dynamically mapping the *up–down* and the *left–right* schema. Using these two space schemas, users can make any two-dimensional directional movements, such as north, south or south-west. (Making accurate 3D movements would require the use of an additional *front-back* schema. While physical tokens allow tangible interactions to use the *front-back* schema, absence of haptic feedback in touchless interactions limits the use of that space schema.) To leverage the up–down and the left–right space schemas, a touchless system would provide visual cues on a 2D display and use orthographic projection to interpret users' 3D hand movements as 2D trajectories. This design proposal opens up a number of questions. Most importantly, given that the sensorimotor knowledge is constant across different directions, *what other factors could affect such mid-air movements*? How will different directions affect users' performance? Will users be more effective with smaller strokes?

4.3. Effect of biomechanical factors on mid-air directional strokes

Our proposed motor-intuitive, touchless interaction primitive is based on space schemas that use the sensorimotor level of knowledge. In touchless interactions, user performance depends on both the level of knowledge at play and biomechanical properties of the human body. To investigate how biomechanical properties can affect a motor-intuitive, touchless primitive, we designed a controlled experiment. Theoretically, users can make any two-dimensional directional movements using the two space schemas left–right and up–down. For our controlled experiment, participants performed mid-air strokes in eight compass directions while sitting away and interacting with a large display. The directions of movement were represented visually on the display to leverage users' sensorimotor skills (image schemas; for details see the Tasks and Procedure section). In our study, we were specifically interested to understand how directions of movement and stroke lengths affect user performance of mid-air strokes. Our experiment did not investigate intuitiveness in touchless interactions (as studied by Aigner *et al.*, 2012; Grandhi *et al.*, 2011; Hespanhol *et al.*, 2012,), but explored how the same motor-intuitive, interaction primitive can cause different user performance (operationalized as effectiveness and efficiency). We did not measure users' self-reported satisfaction because during our pilot studies most users reported equal preferences for all directions of movement and stroke lengths. However, we cite and discuss another work that compared a touchless command-selection technique based on our proposed interaction primitive and 'grab' gestures (see Discussion section).

4.4. Evaluating user performance of mid-air directional strokes

When we move our arms in mid-air, biomechanical properties of the human body (such as position of the forearm relative to the upper body) affect how accurately and quickly we can make arm movements (Werner *et al.*, 1997). Although empirical studies suggest that hand-pointing at shoulder level requires more effort than pointing at center level, no significant effects of arm-configuration or arm-extension on performance time (efficiency) or accuracy (effectiveness) has been reported (Hincapié-Ramos *et al.*, 2014). Because of the required effort, we argue that arm postures will affect the efficiency and accuracy of hand movements.

Hypothesis 1 (H1): Direction of movement will affect the efficiency of mid-air directional strokes.

Hypothesis 2 (H2): Direction of movement will affect the effectiveness of mid-air directional strokes.

Pointing and target acquisition has been widely studied in device-based input modalities (Grossman and Balakrishnan, 2004; Fitts, 1954; MacKenzie and Buxton, 1992; Shoemaker *et al.*, 2012). It is well established in the literature that time taken to complete a movement is directly proportional to the amplitude of the movement. Moreover, Nancel *et al.* (2011) found that unguided mid-air gestures are more tiring than device-based mid-air gestures, which suggests that users would be more precise with smaller amplitude of movements.

Hypothesis 3 (H3): Increase in stroke length will decrease the efficiency of mid-air directional strokes.

Hypothesis 4 (H4): Increase in a stroke length will decrease the effectiveness of mid-air directional strokes.

5. METHOD

We conducted a within-subject experiment to understand how well participants can perform mid-air strokes in different directions. Specifically, we wanted to test the effect of direction and stroke length on the efficiency and effectiveness of mid-air strokes. Furthermore, we wanted to compare the paths that participants took across different directions and stroke lengths. This important data can inform future research on designing touchless interfaces that draw on dynamic gestures.

5.1. Participants

We recruited 17 right-handed participants (7 females) from an urban university campus. Ten participants had prior familiarity with touchless gestures. Twelve participants were below 30 years of age. Participants were randomly recruited by sending out emails using the university's mailing list. The study was approved by the Indiana University Institutional Review Board (Protocol# 1303010855), and participants were compensated with a $20 gift card for an hour of participation.

5.2. Apparatus

We used a high-resolution large display integrated by Fakespace Systems that comprises of eight 1.27 m projection cubes laid out in a 4×2 matrix. It is driven by a single computer. Each cube has a resolution of 1600×1200 pixels, resulting in a 4.06 m wide by 1.52 m high display with over 15.3 million pixels. We used a Kinect™ for Windows to track users' hand position. The experiments were written in C# running on Windows 7, and were implemented with OpenNI 1.4 SDK and PrimeSense's NITE 1.5.

5.3. Tasks and procedure

To test our hypotheses, we designed an experimental task (Fig. 4, right) inspired by a previous study (Lepinski *et al.*, 2010). On a large interactive display (Fig. 4, left), participants were

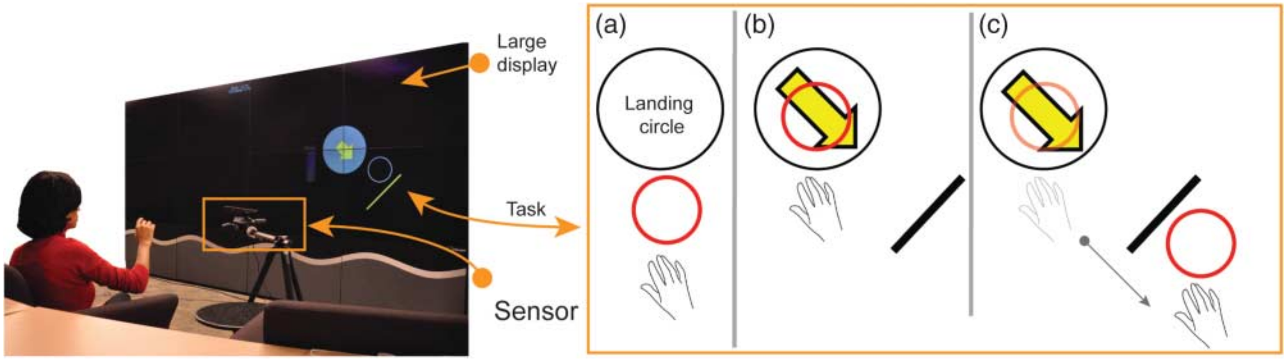

Figure 4. (Left) In our experiment, participants used touchless gestures to interact with a large display, while sitting away from it. (Right) The experimental task began with a landing circle appearing on the display (a). As participants reached the landing circle, the direction of movement and the target line appeared (b). Participants completed the task by making a directional stroke with a minimum travel distance as informed by the target line (c).

presented with a direction (at random) and a target line in that direction. The (640-pixel long) target line informed users of the minimum travel length and appeared at 500, 800 or 1100 pixels. Participants were situated 1 m away from the sensor and were asked to make a hand movement in the provided direction as accurately as possible. The motion-tracking sensor had a horizontal field of view of 57° and a vertical field of view of 43°. Participants' movements were mapped from real space to display space as 1:3.7 (when a participant moved 1 cm in real space the cursor moved 3.7 cm in the display space). Trajectory lengths in real space were 86, 137 and 189 mm. We chose smaller movements, because a survey on social acceptability of touchless gestures (Bragdon *et al.*, 2011) found that 80% of respondents felt comfortable performing smaller hand motions over larger body motions, such as sweeping their arms well across their body. Eight different directions were presented at random: 0, 45, 90, 135, 180, 225, 270 and 360°.

Participants sat in a comfortable couch at 2.25 m away from the large display and took about 20–30 min to complete all trials. Existing studies on touchless interaction with large displays have mostly investigated settings where users are standing in front of the display. However, a sitting posture may limit users' fluidity of hand-movements more than a standing posture. We chose a sitting position for our experiments to avoid standing fatigue and uncover any limitations posed by a sitting posture. Trials were recorded using a video camera capturing users' gestures and the display. Before the actual experiment, all participants completed three blocks of practice trials. Participants were required to take at least a 10-s break in between each block. Trials were randomized within subjects. In summary, the study design was as followed:

$$8 \text{ directions (trials)} \times 3 \text{ trajectory lengths} \times 5 \text{ blocks} \times 17 \text{ participants} = 2040 \text{ trials}$$

Participants hovered over a 'Start' circle to begin a block. Each trial began with a *landing circle* appearing on the display, which participants landed on to begin the trial. The landing circle was horizontally aligned with the participants' body midline, and 142 cm from the ground. The sensor was 84 cm from the ground, and the couch-seat was 44 cm high. As soon as participants reached the landing circle, two things would appear: an arrow representing one out of eight directions and a *target line* at one of the three stroke lengths (Fig. 4). For a trial to be considered successful, participants were required to move past the target line with an angular error less than 45°. Participants' hand movements in the 3D space were measured as their orthographic projections on the 2D display. (A video demonstrating the experimental procedure with an expert user is available in Supplementary Material.)

5.4. Measures

We recorded performance time, error rate, angular error and trajectory paths. Time was measured from when participants left the landing circle to when they moved past the target line. We measured the stroke angle using the last point recorded inside the landing circle and the first point recorded after crossing the target line (hence the target line, though 20-pixel wide, did not influence the calculation of angular error). Angular error was calculated as the absolute difference between this stroke angle and the required angle for the trial. An error was recorded when the angular error was more than 45°. In the case of an error, the trial was repeated until participants successfully completed it. We measured efficiency as time to complete a trial and effectiveness as error rates and angular error.

6. RESULTS

Performance data were analyzed using nonparametric tests for within-subject experimental design because Shapiro–Wilk tests were significant, $P < 0.001$, and Q-Q plots were non-linear. In our experimental setup, participants sat in a couch away from

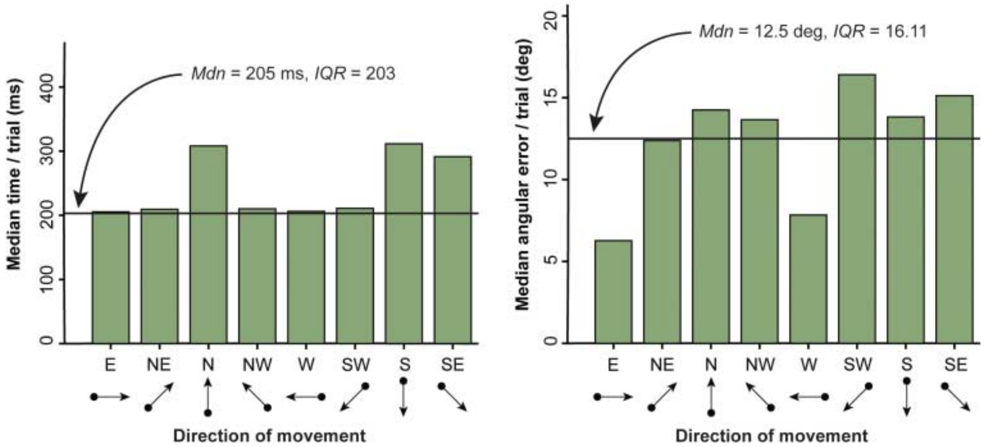

Figure 5. Direction of movement significantly affected performance time and angular error of mid-air strokes, $P < 0.001$. Participants made significantly less angular error ($P < 0.001$) in E and W direction compared with all other directions (NE, N, NW, SW, S and SE).

the large display (Fig. 4). We observed that some participants ran into considerable ergonomic constraints in making movements in the south direction (270°) because of the sitting posture. Their arm movements got hindered by their knees or the armrest of the couch (more in Limitations). This effect is obvious in all of our following results. To ensure that this experimental artifact would not affect the conclusions we draw from our results, we also tested our data without considering the S-direction as one of the levels of the direction variable. When these tests showed major differences in terms of the significance level, we reported the test statistic and the level of significance.

6.1. Direction of movement affects efficiency and effectiveness of mid-air strokes

Direction of movement significantly affected performance time (median = 205 ms, IQR = 203), $\chi^2(7) = 146.93$, $P < 0.001$ (Fig. 5). We conducted 13 pairwise comparisons: N vs. rest of the directions, and S vs. rest of the directions. *Post hoc* Wilcoxon signed-rank tests (with *Bonferroni* correction, significance level 0.0038) revealed that participants took significantly more time making strokes in N-direction than E, W, NE or NW, $P < 0.001$, with a medium effect, $0.33 < r < 0.46$. We found a significant learning effect across blocks, $P < 0.01$. Participants were about 66 ms faster in the last block than in the first block. $H1$ was supported.

A trial was considered erroneous, when participants made an angular error more than 45° in clockwise or counter-clockwise direction. Direction of movement significantly affected error rate (median = 4.76%, IQR = 7.08), $\chi^2(7) = 28.82$, $P < 0.001$ (without S-direction, $\chi^2(6) = 20.7$, $P < 0.01$).

Direction of movement significantly affected angular error (median = 12.5°, IQR = 16.11), $\chi^2(7) = 159.14$, $P < 0.001$. We conducted 13 pairwise comparisons: E vs. rest of the directions and W vs. rest of the directions (with *Bonferroni* correction, significance level 0.0038). *Post hoc* Wilcoxon signed-rank tests revealed that angular error in directions N, NE, NW, S, SE and SW were significantly more than angular error in E direction, $P < 0.001$, with a medium effect, $0.37 < r < 0.50$; and in W direction, $P < 0.001$, with a small to medium effect, $0.28 < r < 0.44$. Angular error was more in W direction (median = 7.00°) than in E direction (median = 8.60°), $Z = 2.08$, but not significant, $P = 0.04$. $H2$ was supported.

6.2. Stroke length affects efficiency and effectiveness of mid-air strokes

Stroke length significantly affected performance time, $\chi^2(2) = 385.39$, $P < 0.001$ (Fig. 6). *Post hoc* Wilcoxon signed-rank tests (with *Bonferroni* correction, significance level 0.016) revealed that performance time was significantly different between each pair of distances, $P < 0.001$. Small stroke length (median = 105 ms, IQR = 28.7) was significantly faster than medium stroke length (median = 205 ms, IQR = 182.12) with a medium effect, $Z = 13.48$, $P < 0.001$, $r = 0.47$; and medium stroke length was significantly faster than large stroke length (median = 309 ms, IQR = 230.63) with a medium effect, $Z = 12.44$, $P < 0.001$, $r = 0.44$. $H3$ was supported.

Stroke length did not significantly affect error rate, but significantly affected angular error, $\chi^2(2) = 42.19$, $P < 0.001$ (without the S-direction: $\chi^2(2) = 34.66$, $P < 0.001$). Moreover, *post hoc* tests revealed that angular error significantly decreased with increase in stroke lengths. Angular error for small strokes (median = 15.1°, IQR = 17.61) was significantly more than angular error for medium strokes (median = 12°, IQR = 15.74) with a small effect, $Z = 4.44$, $P < 0.001$, $r = 0.13$; angular error for medium strokes was significantly more than angular error for large strokes (median = 10.68, IQR = 12.4) with a small effect, $Z = 4.04$, $P < 0.001$, $r = 0.11$. $H4$ was not supported.

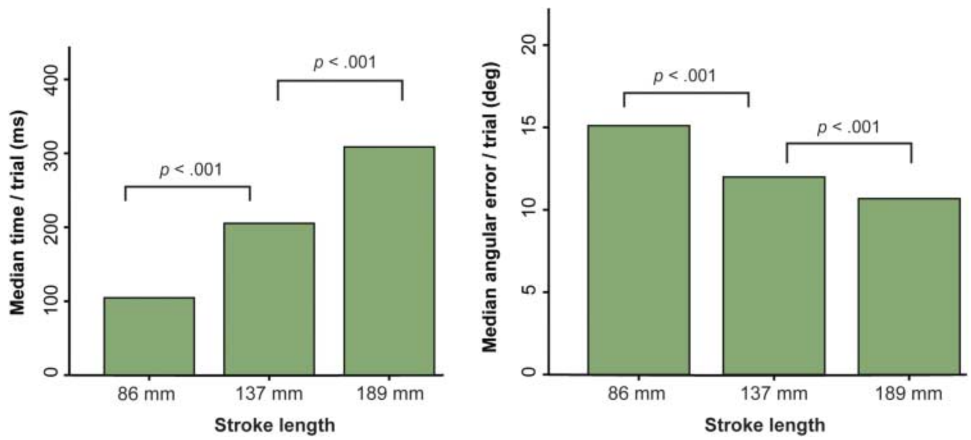

Figure 6. Stroke length significantly affected performance time and angular error of mid-air strokes, $P < 0.001$. Interestingly, participants made significantly less angular error with increase in stroke length, $P < 0.001$.

6.3. Trajectory patterns indicate asymmetric ability in touchless interactions

We recorded the paths participants took to move in different directions across different stroke lengths (Fig. 7). Participants were asked to make directional strokes as accurately as possible. We recorded paths only for successful trials, and a trial was successful if a participant's angular error was less than 45°. From the visualization of these paths, a number of patterns emerged. First, participants' trajectories were longer in their dominant side compared with their non-dominant side. Second, confirming previous findings, their angular error decreased as stroke length increased. Third, we observed a trend in participants' hand movements towards the eastern hemisphere (dominant side) and the northern hemisphere. For example, in both N and S direction of movement, participants' strokes tended towards the eastern hemisphere; in E and W direction, their strokes tended towards the northern hemisphere.

In the following section, we discuss the lessons learned from our experiments, and the implications suggested by our findings. Specifically, we discuss how our findings can inform the design of intuitive touchless interactions and UI elements for large-display touchless interactions (such as menus, or toolbars).

7. DISCUSSION

In this paper, we introduced motor-intuitive, touchless interactions based on image schemas that draw on our sensorimotor level of knowledge. To illustrate our concept, we proposed a motor-intuitive, touchless interaction primitive: mid-air directional strokes mapping the *up–down* and the *left–right* space schemas. We then argued that in touchless interactions, a motor-intuitive primitive is affected by the biomechanical properties of the human body. To that aim, we explored how the same motor-intuitive, interaction primitive can result in different user performance across different directions of movement and different stroke lengths.

7.1. Lessons learned

In a controlled experiment ($n = 17$), we investigated efficiency and effectiveness of mid-air strokes. We learned the following from our study. First, direction of movement significantly affected efficiency and angular error of mid-air strokes. On average, participants were very efficient and took only 0.2 s (median performance time) to make a directional stroke. However, their median angular error was 12.5°, which is slightly more than twice compared with a previous study on multitouch strokes (5.6°, Lepinski *et al.*, 2010). Increase in angular error from multitouch to mid-air strokes contradicts a previous finding, where 2D surface gestures were more erroneous than 3D-free gestures (Nancel *et al.*, 2011). However, such a comparison is limited, because these studies used different experimental tasks and settings. Previous studies that explored 3D strokes as interaction commands (Guimbretière and Nguyen, 2012; Ren and O'Neill, 2012) do not report any performance measures because users were extremely inaccurate. Instead, the gesture primitives were either redefined or reported as infeasible. Unlike accurate 3D strokes (based on the expertise level of knowledge), we found 2D directional strokes (based on the image schemas, which is a sensorimotor level of knowledge) generally effective and efficient. This supports our premise that the intuitiveness of touchless interactions can be operationalized using the continuum of knowledge in intuitive interaction (Hurtienne and Israel, 2007): the higher the level of knowledge used in an interaction primitive, the lower would be the expected speed of knowledge retrieval and the lesser would be the primitive's intuitiveness to general population.

Second, increase in stroke length increased performance time. This is an expected result that aligns well with previous findings for other input modalities, where movement time

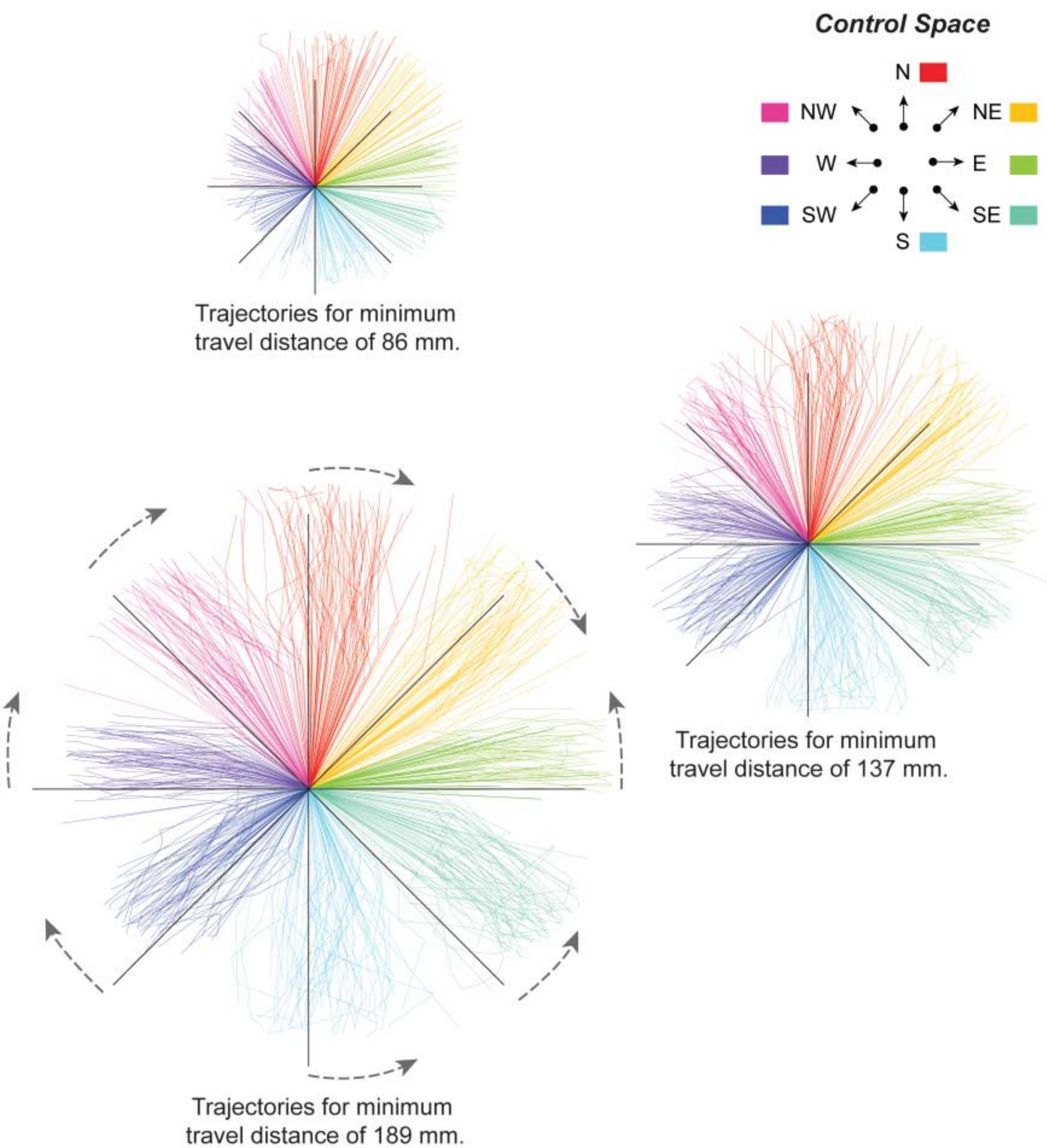

Figure 7. We recorded trajectories (across eight directions and three distances) from 17 right-handed participants as they performed directional strokes in mid-air (see Fig. 4). In right-handed users' control space, we observed the following: (a) participants performed longer trajectories while operating in their dominant side than in their non-dominant side; (b) participants' angular error decreased with an increase in the stroke length (similar to Fig. 6); and (c) participants' hand movements tended towards the eastern hemisphere and the northern hemisphere (illustrated by dashed arrows).

increased with movement amplitude (Fitts, 1954; MacKenzie and Buxton, 1992). Increase in stroke length also decreased angular error. This is an unexpected finding that suggests that we tend to over-correct our movements based on forward planning (Shadmehr *et al.*, 2010). This finding advises against designing touchless gestures that require users to make directional strokes with a very short trajectory length (more in the Design Implications).

Third, we found an effect of cross-lateral inhibition on user's ability to make mid-air strokes. Cross-lateral inhibition occurs when users' hand crosses the body midline and operates away from their dominant side (Fig. 8): crossing the 'body midline' offers more resistance than operations limited to the same side of the dominant hand (Schofield, 1976). In line with this biomechanical property, we observed that across all stroke lengths, right-handed participants made longer strokes

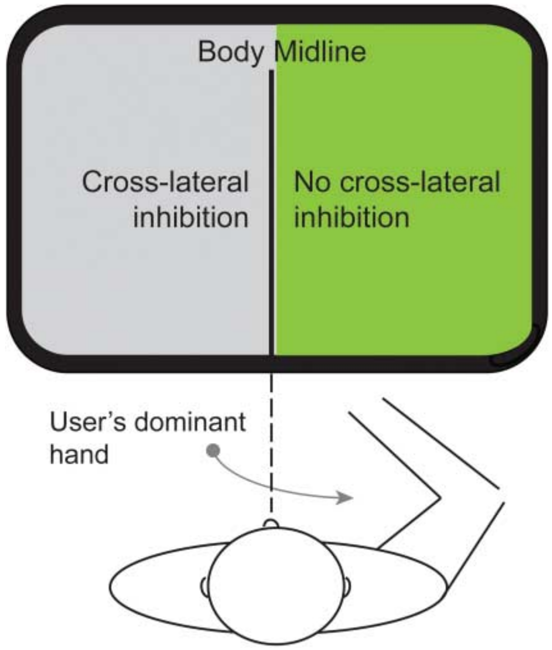

Figure 8. Cross-lateral inhibition occurs when users' hand crosses the body midline and operates away from their dominant side (e.g., left side for right-handed participants).

on their dominant side (Fig. 7). However, we did not find any significant effect of cross-lateral inhibition on users' efficiency or effectiveness. This effect of cross-lateral inhibition indicates how handedness—an innate level of knowledge—affected an interaction primitive that used the sensorimotor level of knowledge. This observation follows the inherent dimensionality of the continuum of knowledge in intuitive interaction: the lower the level of knowledge the higher the frequency of encoding and retrieval of knowledge. Hence, interaction primitives designed to use any particular level of knowledge in the continuum would still be affected by the levels of knowledge residing below (in varied amounts based on prior use and training).

Overall, our findings suggest that in intuitive touchless interactions, user performance of a motor-intuitive, touchless primitive is significantly affected by the biomechanical properties of the human body. Based on efficiency, angular errors and the trajectory-patterns that participants took to make directional strokes in mid-air, we identified three regions that are characterized by decreasing performance and increasing effort: top-right, top-left and top-middle (Fig. 9). Our findings align with previous results where researchers found that users' physical effort was significantly more for interactions in the shoulder plane (similar to our top-middle) compared with interactions in the center plane (similar to our top-left and top-right) (Hincapié-Ramos *et al.*, 2014). We do not comment on users' relative performance in the southern hemisphere, because we observed that our experimental setting constrained some users' southward movements. Hence, the relatively inferior user performance may be an artifact of our experiment. In the following paragraphs, we use our findings to inform some design implications for both intuitive touchless interactions and large-display touchless interactions.

7.2. Design implications

7.2.1. *Design implications for intuitive touchless interactions*

Compared with previous reports on users' failure to perform 3D trajectories as interaction commands, we found that mid-air directional movements based on image schemas (*up–down* and *left–right*) were efficient (median 0.2 s) and effective (median angular error of 12.5°). We did not record users' self-reported satisfaction, because during our pilot studies most users reported equal preferences across all experimental conditions. Such equal preferences can be explained by the same level of knowledge at play (sensorimotor level) during interacting in different directions and different stroke lengths. To compare a motor-intuitive touchless primitive with another gesture primitive, Chattopadhyay and Bolchini (2014) introduced a command-selection technique based on mid-air directional strokes (Touchless Circular Menus). In a controlled study, they found that touchless circular menus were twice more efficient than linear menus that used 'grab' gestures; users also perceived less workload while using the touchless circular menus.

Our empirical results suggest that in touchless interaction, *intuitive interaction* depends on both the sensorimotor level

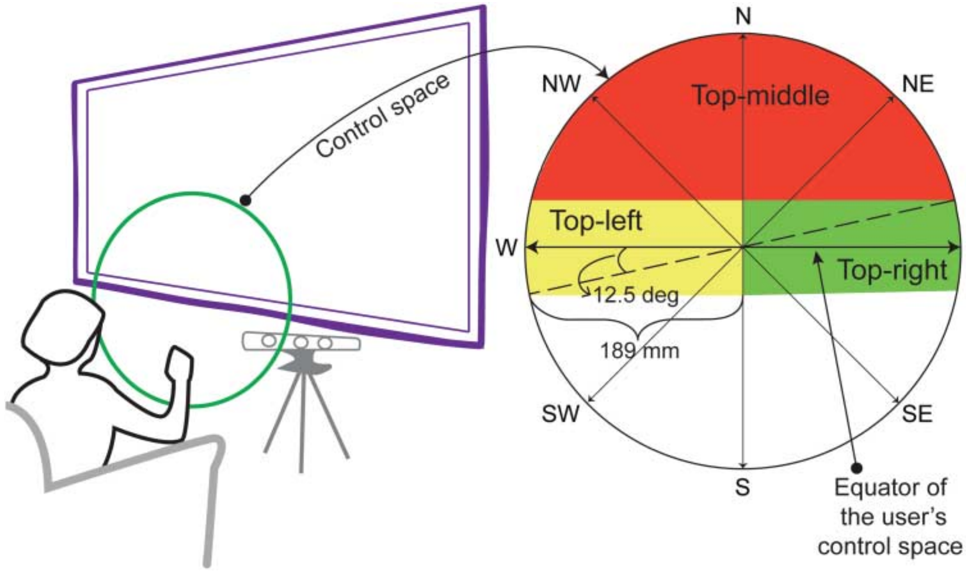

Figure 9. In a right-handed user's control space, while sitting away and interacting with a large display, our study on mid-air directional strokes identified three regions that are characterized by decreasing performance and increasing effort: top-right, top-left and top-middle.

of knowledge and the biomechanical properties of the body. We showed that even when touchless interactions with mid-air strokes draw on the sensorimotor level of knowledge, other factors such as directions of movement and stroke lengths significantly affect the user performance. Specifically, we present two design guidelines for intuitive touchless interaction. First, scale-dependent, directional gestures should not be of very small length (e.g. 86 mm in our experiment) because though such gestures take less time to complete, they seem to produce more angular error. Instead, designers should consider selecting a stroke length that involves more than just flipping the hand, such as moving the forearm (portion of users' arm between the elbow and the wrist), because longer strokes are more accurate. However, it must be noted that large hand-movements sweeping across the body has been reported as fatiguing and socially unacceptable (Bragdon *et al.*, 2011). Hence, large hand-movements requiring users to move their arm (not just forearm) might be more effective but would be less efficient and less acceptable to users in a specific context.

Second, dynamic touchless gestures should only require users to make 2D directional strokes, rather than accurate angular movements in 3D. For example, a menu option should be accessible by making a stroke in any compass direction (such as NE or SW) that is based on space schemas (up–down or left–right), rather than a three-dimensional angle in freespace (such as vectors in 3D space, cf. Fig. 5 in Guimbretière and Nguyen, 2012). Continuous visual feedback to guide users in making such directional gestures will be helpful. For example, rather than depending on users' proprioception to execute mid-air strokes (Guimbretière and Nguyen, 2012), a dynamic illustration (e.g. a visual trace) of how users' hand is moving could be shown (Chattopadhyay and Bolchini, 2014). In general, visual feedback is a major factor affecting the intuitiveness of touchless interactions.

In the absence of any haptic feedback, visual feedback plays a major role to ensure that while interacting with motor-intuitive touchless primitives, users are actually drawing upon their sensorimotor level of knowledge. For example, it is crucial to provide a proper visual representation of an image schema on the display (e.g. Fig. 4) and adopt an effective frame of reference (egocentric or allocentric, Klatzky, 1998). Our experiments used an allocentric (viewer's) frame of reference and traditional GUI-type visual feedback because the alternative—egocentric frame of reference and full-body avatar visualization—may not be suitable in certain scenarios, such as visualization or collaborative work (Dostal *et al.*, 2014; Bragdon *et al.*, 2011). Because egocentric frame of reference and avatars is used in immersive full-body games, touchless interactions in those games need not be grounded on image schemas to feel intuitive. However, in more traditional settings, touchless primitives based on image schemas will be more intuitive than primitives based on expertise level of knowledge. While we do not discuss the role of visual feedback in touchless interactions in this paper, the effect of visual feedback on acquiring, learning and retaining motor actions is well studied (e.g. see Sigrist *et al.*, 2013).

7.2.2. *Design implications for large-display touchless interactions*

Our findings can also be leveraged to design interface elements for large-display touchless UIs. First, directional strokes to trigger frequently used commands should be in the top-right or the top-left of the user because users' performance suffers as they operate in the top-middle of their control space (see Fig. 9). Moreover, user effort increases as the dominant hand suffers from cross-lateral inhibition when it crosses the body midline (Fig. 8). Designers can leverage this characterization of users' control-space to define rarely used gestures. For example, to operate a media player, users could make a stroke in E-direction to play/pause, and a stroke in N-direction to quit the media player. Similarly, crucial interface widgets such as toolbars should be around the equator of the users' control space (see Fig. 9) because we found that users were most effective and efficient in executing mid-air strokes around the equator.

Second, the average angular error of 12.5° in mid-air directional strokes suggests that pie-based touchless menus can offer about 25 command-selection options that can still be accurately selected with mid-air strokes. Future controlled experiments can be informed by this range of touchless menu options to further determine the precise cardinality of menu items. Apart from menus, mid-air directional strokes will also play an important role as an interaction primitive in touchless user interfaces for sketching (Taele and Hammond, 2014).

Finally, our experiment with a large display explored intuitiveness of touchless primitives that leverage the entire control space available for hand gestures. Hand gestures when used with current game consoles only involve a small control space (i.e. users' hand movements are very small and directly in front of the sensor) because users are situated about 2–3 m away from a 1.27 m HDTV. In comparison, large-display interaction opens up the potential of a larger control space. In our work, we showed how using a larger control space poses new limitations to touchless interactions, such as biomechanical factors, even when a gesture primitive is based on our sensorimotor level of knowledge (motor-intuitive). Furthermore, we argue that motor-intuitive, touchless interactions will outperform expertise-based interactions because touchless interactions are sporadic, spontaneous and short-lived: They are often used for exploratory tasks (e.g. browsing images, opening and closing files, or using media controls) rather than fine-grained, repetitious tasks (e.g. editing) (Chattopadhyay and Bolchini, 2013).

7.3. Limitations

Our experiment was limited by the capabilities of our motion-tracking sensor, which operated at a refresh rate of 30 frames per second. We could not record some of the trajectory paths (Fig. 7), because some tracking points were lost when participants moved their hands very fast. We also placed our sensor in such a way that the execution of the longest stroke was within the sensor's optimal tracking range. Our experimental setup also limits our findings. Specifically, we observed that some of our participants faced considerable ergonomic constraints while performing southward movements. We chose a 'sitting' position for our experiments to avoid users' standing fatigue. We did not anticipate that users would face ergonomic constraints in this position, but users often moved their hands backward (towards the center of their body) instead of southward, thus causing the arm-rest to restrain their movements.

For small-length strokes, some users completed an entire experimental trial in the E and the W direction while resting their hands on the arm rest. This was not possible for trials in any other direction, with medium or large strokes. While those few trials may have increased the efficiency and effectiveness of mid-air strokes in E and W direction, they do not confound our general conclusion that biomechanical factors affect motor-intuitive, touchless interactions. Furthermore, other experiments using a standing posture and without any armrest has also shown that touchless interactions in the center plane (e.g. E and W) requires significantly less effort than interactions in the shoulder plane (e.g. N, S or NW). In addition, all our participants were right-handed. Hence, we cannot claim a generalization of our findings across left-handed users.

We did not investigate the effect of control-display gain or pointer acceleration on the execution of mid-air strokes. This would be necessary to design the required length of mid-air strokes in a touchless interface. We anticipate an effect of pointer-acceleration on user performance of mid-air strokes. Furthermore, we did not record any subjective ratings for user fatigue or intuitiveness. Informally, users did not report significant physical strain after a block of execution of mid-air strokes.

We need to further consider the role of visual feedback in guiding users to make mid-air strokes. In our study, the direction of movement was presented as a static image. Users mentioned that a dynamic illustration of their hand movement would be helpful in making accurate strokes. We think that adequate visual feedback will somewhat mitigate the absence of haptic feedback, and also improve users' learnability. However, this needs to be further explored.

Though we mention that the median angular error for mid-air, directional strokes—12.5°—can inform the design of touchless pie-menus, future experiments are required to identify the precise cardinality of such menus. Moreover, in our experiments, we used a landing circle to mark the beginning of a mid-air stroke. It is necessary to investigate specific invocation techniques when such dynamic gestures are applied to touchless interfaces.

7.4. External validity

Our findings can be generalized to touchless interaction settings, where users are sitting away from a large display, facing the display and within the sensor's tracking range. Though our study used a couch with an arm-rest (see Fig. 4), our findings can be extended to other furniture setups. However, it must be noted that an arm-rest in such scenarios plays a two-fold role: (a) it can help reduce user-fatigue by allowing the elbow to rest during hand movements; (b) it can also constrain southward movements. Since sitting posture already constrained users' hand movements to a certain extent, we expect our general findings to stay valid in a standing posture. For example, 2D strokes would be more intuitive than 3D strokes without prior expertise and directions of strokes and stroke-length would still affect the user performance of mid-air strokes. However, in a standing posture, users would be more efficient in utilizing the southern hemisphere of their control space than while sitting. Finally, our design guidelines are agnostic of the control-display gain of the system, or how the control space is mapped to the display space. We provided insights into how human sensorimotor abilities (in the control space) can inform the design of intuitive touchless interfaces (in the display space).

8. CONCLUSIONS

How intuitively users perform a mid-air hand gesture can inform what subset of physically possible actions should constitute intuitive touchless interactions. For example, in this paper we contrasted between two touchless gesture primitives—making accurate 3D strokes that draw on the expertise level of knowledge and making 2D directional strokes that draw on the sensorimotor level of knowledge. The fact that making accurate 3D strokes is less intuitive for the general population than making 2D strokes can be explained by the intuitive interaction framework where the expertise level of knowledge resides above the sensorimotor level. Hence, we argued that the *continuum of knowledge in intuitive interaction* can operationalize the intuitiveness of touchless interfaces because it informs the design of touchless primitives by considering the level of knowledge that is at play during their execution. Specifically, we introduced motor-intuitive, touchless interactions based on image schemas that draw on our sensorimotor level of knowledge. To illustrate motor-intuitive interactions, we proposed a touchless primitive—mid-air, directional strokes—based on space schemas *up–down* and *left–right*. We then investigated how our proposed touchless primitive is affected by the biomechanical properties of the human body.

Our findings suggest that mid-air (2D) directional strokes are efficient (median time of 0.2 s) and effective (median angular error of 12.5°). From our results, we discovered that directions of movement (2D) and stroke length affect users' performance of mid-air directional strokes. Interestingly, users made significantly accurate strokes while travelling longer trajectories. While sitting away and interacting with a large display, our results identified three regions in a right-handed user's control space that can be characterized by decreasing accuracy and increasing effort: top-right, top-left and top-middle. Finally, grounded in our findings, we provided practical guidelines on designing intuitive touchless interaction and UI elements for large displays.

This is but a first step in understanding how the continuum of knowledge in intuitive interaction can inform the design of motor-intuitive, touchless interaction primitives. Our findings can inform fundamental design decisions to align touchless user interfaces with human sensorimotor abilities, thus making them intuitive to use. An important result from this study is how asymmetric motor abilities—due to biomechanical factors—affect user performance of motor-intuitive, touchless interactions.

Among the many research directions that this work opens up, we are investigating two lines of inquiry. First, we are leveraging the notion of asymmetric abilities to design appropriate touchless user interface elements, such as novel menus and toolbars. Second, given the crucial role of visual feedback in facilitating the knowledge-retrieval from different levels of knowledge (sensorimotor, expertise or tools), we are deepening our understanding of visual feedback in touchless interactions.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *www.iwc.oxfordjournals.org*.

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