Conveying Feedback in Skill Movement Acquisition

Master's Thesis at the
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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

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Aachen, July2015
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Abstract

Acquiring a coordinated fine motor skill involves exploring the work space of the task that can be best achieved in the presence of an expert or teacher. The teacher helps the learner channel the movements towards the accurate actions required for the task by giving the learner appropriate feedback. In the absence of the teacher, this critical exchange disappears and the learner is left to overcome the gaps on his own or with graphics such as images and videos. Recently, due to improvement in technology, research in the area of technology assisted learning and associated feedback has gained a lot of momentum in Human Computer Interaction. The studies in this field so far have brought forward new techniques or methods to help the learner perform a certain motor task such as dancing or rehabilitation.

We present an approach for determining the performance measurement criteria for a skill and designing appropriate low-level corrective feedback based on the evaluation. For the purpose of this thesis we have chosen the task of knife honing. For arriving at the criteria we took a comprehensive look at the taxonomy of skills, feedback, human movement pattern and studied the expert's movements in action. To address the design concerns and choices, and to assist in the designing of the feedback visualizations, we also present a Dimension Space. Lastly, we conduct a user study to compare the designed feedback visualizations with videos to gain insight about their correctness and ability to convey required information to help the learner improve his mistakes.

Acknowledgements

Firstly, I would like to thank Prof. Jan Borchers for giving me the opportunity to undertake such a wonderful project at the chair. This thesis has made me learn so much about the fundamentals of not only Human Computer Interaction, but also Motor Learning and Augmented Reality.

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Conventions

Throughout this thesis we use the following conventions.

The whole thesis is written in American English

Irrespective of the real users' gender we will use "he" as a reference to a single person.

Chapter 1

Introduction

Importance of feedback in skill acquisition and need for systems which provide feedback in the absence of an instructor

Training in psycho-motor skills (related to one's physical movement and coordination) is an area of on-going research in the field of Human Computer Interaction. The process of traditional training for acquiring such a skill includes the demonstration of the skill by the instructor, the performance by the learner and ultimately the feedback or the performance assessment by the instructor. Initially, the learner will lack proficiency, but this can be improved by training under the guidance of an instructor. Instructor's guidance or feedback is usually seen as the means to maximize learning and induce long-term retention. When the learner is not in the company of the instructor the critical exchange of feedback disappears, but can be managed through videos and images. However, such media can not provide feedback to the degree of accuracy which is critical for improving the level of efficiency in learning. Many studies (Weing et al. [2013], Mitobe et al. [2012], Anderson et al. [2013], Sodhi et al. [2012], Xiao and Ishii [2011]) in HCI have explored methods of communicating movement patterns and appropriate feedback to help the learner acquire different skills, such as playing the piano, playing the koto (Japanese harp), dancing and abstract hand movements, in the absence of an instructor.

Skill classification and the challenges in skill training

Apart from pyscho-motor skills, from motor learning literature (Anderson et al. [2001]) we know that, there are two other categories of skills — cognitive (related to person's intellect and knowledge) and affective (related to an individual's emotional quotient). We must understand that any ability that can be called skilled involves combinations of cognitive, affective, and motor processes with different weights. Therefore, although the research in HCI in this field is primarily concerned with the development of skills in the psycho-motor domain, the growth of these skills is influenced by the learner's knowledge, attitude and environment. This makes the process of training a complicated one. To further add to this difficulty a majority of the motor skills involve some degree of collaboration between the hands. Our hands allow us to perform several sophisticated and difficult activities such as using tools, gesturing, typing and writing. Thus, this type of skill acquisition involves not only the learning of adaptive patterns of muscular movements and timing, but also understanding of the context and control required while performing the movements.

Our interest is vested in performance feature evaluation for designing feedback

To facilitate such learning, different research techniques have been experimented with. For instance, Anderson et al. [2013] recorded the movements of the expert and presented it to the learner on a mirror-like display; the learner then imitated the movements. Subsequently, when the learner made mistakes, he was shown feedback to correct his actions. On the other hand, Mitobe et al. [2012] collected the expert's movement data using a motion capture setup and then presented it to the learner via a head mounted display, such that the learner could see the expert's hand and his own side by side, and imitate the expert's actions. However, majorly these studies focused on bringing forward new methods using different technologies to provide feedback. In this thesis we are interested to understand how we can evaluate the performance features of a skill to design an appropriate visual feedback.

Scope of work

This thesis will explore about performance measurement criteria required to design a visual feedback, which is a good representative of the evaluated performance features. Further, based on the criteria found, an appropriate visual feedback will be designed and analyzed to gauge how helpful the feedback is to the users in performing the movement sequences.

The work starts with giving a taxonomy of skills and feedback to gain some foundation for defining a performance measurement criteria. Since in a system communicating skill movement the actors interact with objects both in the physical and virtual worlds to complete a task, we define a dimension space to describe the design choices available. The dimension space is based on the taxonomy, and is described with the plots and analysis methodologies. Having the dimension space, we take a comprehensive look at how it can be applied to a chosen activity - knife honing. The procedure for defining the performance measurement criteria is discussed which includes discussions with the expert, capture of expert data, capture of data from novice users, annotation of the data and videos captured, and finally the analysis of results. This will give us a concrete idea about the characteristics that feedback visualization must have. Further, based on the dimension space, the work proposes a feedback visualization system for the activity of knife honing. It is a kind of animation visualization which is in accordance with the dimension space and can be generated from the data collected from the user's performance. The visualizations are used to describe sparse mathematical information as the feedback and ultimately evaluate whether it fulfills the requirements of providing critical knowledge about improvement and quality of performance. A user study run by a program is included in this work to support and evaluate the benefit of the visualizations proposed.

This thesis has three main contributions: Thesis contributions

1. We present performance features for the selected skill along with evidence from data collected from novice and expert users. We also describe a dimension space for assisting in making design choices for a system conveying feedback for skill movement acquisition.

2. We design feedback visualizations based on the performance measurement criteria to show the features of the chosen skill — knife honing.

3. We conduct a controlled experiment to analyze how the proposed feedback visualization affects novice users, discover patterns and present results.

Thesis structure

In the points that follow we provide a brief summary of each chapter to give an overall structure of the thesis:

Chapter 2 — "Related work" In this chapter, we provide an overview of other related publicized work which deals with creating a dimension space and design space and novel systems about motor skill acquisition from the perspective of Human Computer Interaction.

Chapter 2 — "Related work" In this chapter, we describe the taxonomy of skills, the different types of feedback along with the basics of human movement and its patterns. Furthermore, we present the dimension space, describe the design concerns, and explain the different axes.

Chapter 4 — "Performance Measurement Criteria and Visualization" In this chapter, we report the apparatus and the procedure for collection of motion data, and the post-processing of data for deciding the performance features. To establish performance measurement criteria, we explain the common mistakes for the task of knife honing and how we have established thresholds for these mistakes. Lastly, we present the visualization based on the criteria and discussion.

Chapter 5 — "User Study" In this chapter, we outline the pilot and main user study with the task of knife honing. In the subsections we describe the results and discussions.

Chapter 6 — "Summary and future work" In this chapter, we summarize the work done in this thesis, discuss the findings and outline the future possibilities.

Chapter 2

Related work

2.1 Design Space

As yet, there has been no research work that is solely dedicated to building a framework or design space for providing feedback for bimanual skill acquisition. The research work done in the field of technology based motor skill learning describes several design choices, but doesn't provide a consolidated foundation from which these design decisions can be made; this is from where the concept of our work originated. There are several published works which have created design spaces for the study of other domains such as information visualization, graphical interfaces and displays. There are also other works which introduce the notion of Dimension Space for describing entities which an interactive system is composed of. From these studies we attempt to understand the process of building a design space for feedback visualization and developing a new design using the same.

Design spaces for information visualization

The foundations of data visualization which include the process of data visualization, optimal visual display and the significance of different kinds of representations which may be a combination of graphical elements and verbal expressions is described in detail in Ware [2012]. Further, this book provides a very interesting note on how animation can enrich any visualization and can be used to powerfully

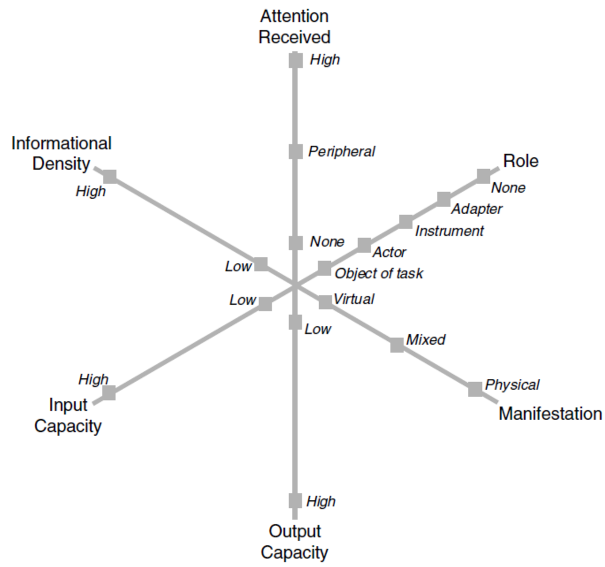


Figure 2.1: Dimension Space Axes (Graham et al. [2000a])

explain the relationships between different kinds of data. Another research which deals with understanding information visualization is Card and Mackinlay [1997]. This paper describes a framework for designing new visualizations for different kinds of data and augmenting existing designs. It suggests the use of table notation to organize the mapping between data and presentation and explains how graphics can be used to map data with visual vocabulary and other characteristics such as color and depth to provide a visualization that is appropriate and can be easily interpreted.

Dimension Space

The idea of Dimension Space Graham et al. [2000a] expands on the approach of Design Space Analysis MacLean and McKerlie [1995]. The notion of Dimension Space was proposed to provide a more methodical way of designing systems which involves interaction between entities from the real and virtual world. This design process represents interactive systems on six axes as shown in Figure 2.1. Birnbaum et al. [2005] provides an account of the application of Dimension space in comparing musical devices with the aim of assisting in designing novel instruments. Figure 2.2 shows the Dimension Space employed by the authors for the said comparison. The study of entities from the point

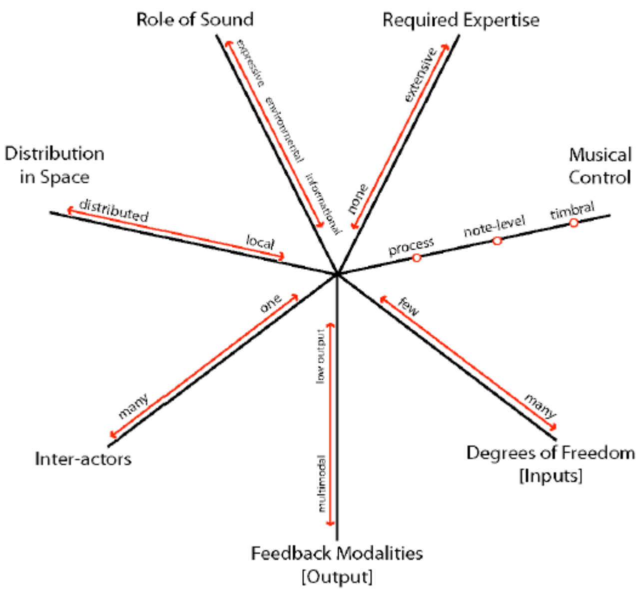


Figure 2.2: 7-axis Dimension Space for Comparing Musical Instruments (Birnbaum et al. [2005])

of view of the dimension space paradigm has helped us to isolate relevant characteristics which will be discussed in Chapter 3 "Taxonomy and Dimension Space".

2.2 Movement Guidance with Technology

Recently a lot of work has been done in the the field of technology assisted learning in Human Computer Interaction. Different researchers have found motivation to provide movement assistance in different fields such as rehabilitation, learning musical instruments and full-body movements.

Guidance derived from expert data

Some of these studies rely on data from experts to provide feedback. The first among studies which depend on expert data to provide appropriate feedback is Mitobe et al. [2012]. In this study guidance is provided to the user with a virtual hand constructed from motion capture data from an expert. The system as shown in Figure 2.3 is aimed at being

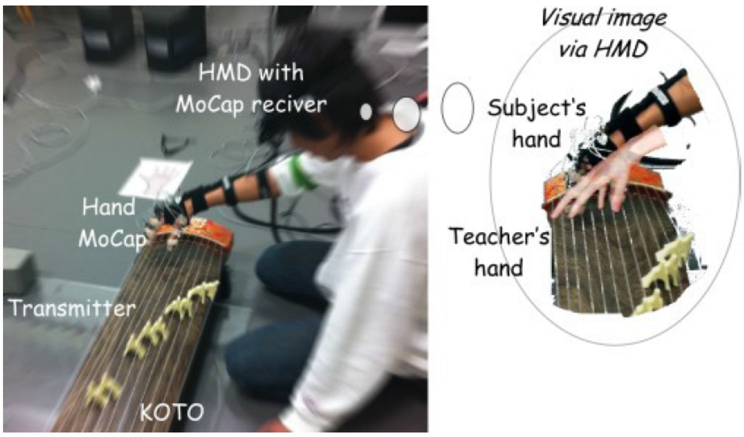


Figure 2.3: Experimental setup for ubiquitous learning system (Mitobe et al. [2012])

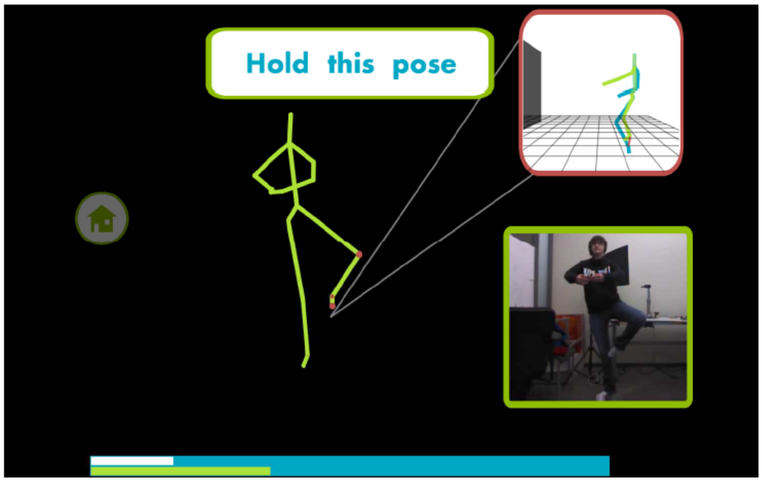


Figure 2.4: Posture guide in YouMove. Errors are highlighted with red circles (Anderson et al. [2013])

a ubiquitous learning system for high precision movements of the hand. The expert's hand movement data is captured using Hand Motion Capture System and shown to the user using a head mounted display as a 3D virtual hand that the user can overlap to learn playing the Koto (Japanese harp). While Mitobe et al. [2012] deals with learning to play an instrument, another study — Anderson et al. [2013] proposes an augmented mirror-like display system called YouMove which provides training based on an expert's

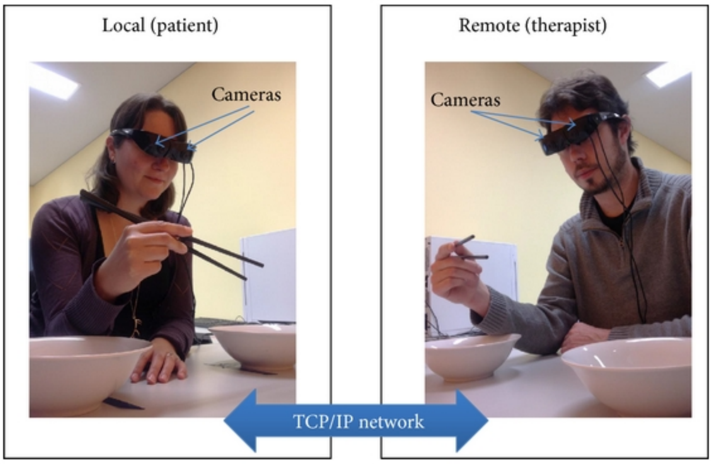


Figure 2.5: Ghostman setup (Chinthammit et al. [2014])

movements. YouMove is a full-body movement instruction system which allows the expert to record and annotate movement sequences using Kinect; these can be used by the trainee for gradually learning the movements using the augmented mirror. Feedback information is provided by comparing the trainee's and the expert's skeleton and it is scored based on the important joints with the maximum error, measured by Euclidean distance. Further, YouMove incorporates posture guidance where the errors are highlighted using red circles as can be seen in Figure 2.4.

Guidance from direct involvement of expert

There are also studies which have direct involvement of the expert. In Chinthammit et al. [2014], the authors have developed an augmented reality system called Ghostman, which focuses on bringing together the therapist (expert) and the patient (user) remotely, to deliver instructions and assess performance. Ghostman comprises of two subsystems, as shown in Figure 2.5, which consist of augmented reality head mounted displays and communicate over the internet. The developers have assumed details about orientation and scaling to simplify their task for conducting the pilot study. Nevertheless, the design principles followed by Ghostman for providing the navigational cue, the ghost image (therapist) and the real-world image (patient), are fundamental. These allow the patient to view

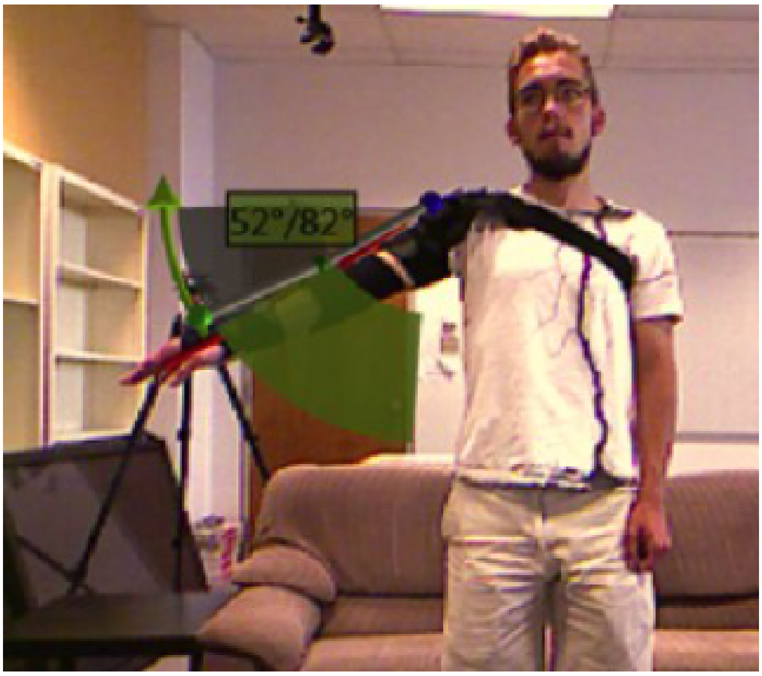


Figure 2.6: Wedge visualization (Tang et al. [2015])

the task at hand from the therapist's point of view which is regarded as "inhabiting visual augmentation". Another research study which has direct involvement of the expert is Zaczynski and Whitehead [2014]. This paper investigates about learning in the domain of interactive gaming and provides design recommendations about the delivery and type of feedback. In the experiments conducted to arrive at the design recommendations, the different conditions of visual feedback were tested such as Front, Front + Wide and so on. For testing the effect of haptic and verbal feedback, the researcher's (expert in yoga poses) touch or voice was used. Pose accuracy during the experiments was judged and scored by the researcher. After their experiments, the authors conclude that providing custom, contextual and multi-modal feedback is the best way to help users resolve errors in their actions.

Guidance in physical rehabilitation

Physical rehabilitation is a common motivation for research in the movement guidance techniques, for patients in the physical absence of a physiotherapist, like in the case of

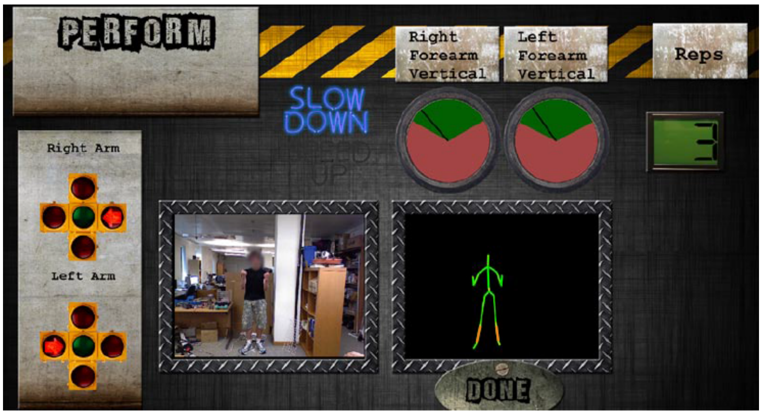


Figure 2.7: Performance interface (Velloso et al. [2013])

Physio@Home Tang et al. [2014, 2015]. In these studies, the authors have designed a system to help patients undergoing physiotherapy using previously recorded exercise sequences. Physio@Home uses Vicon motion tracking cameras and markers on the user's shoulders and arms to capture multiple views of an exercise movement. The prototype guides patients by overlaying visual cues on the mirror-view of the patient. The system uses arrows as feedforward and nearest correct arm as a red stick figure and difference in angle as feedback as shown in Figure 2.6.

Guidance using machine learning

Machine learning has also been leveraged for training movement in the domain of physical fitness as in MotionMA (Velloso et al. [2013]). MotionMA allows a performer to record a repeated movement using the Kinect from which a model is extracted. An observer can then use this model to practice the movement. The observer's actions are recorded by the Kinect, a model is extracted which is compared to the performer's model and real-time feedback is shown to the observer on a display. Tasks such as weight lifting were chosen to test the system developed. The feedback interface is designed such that "Information regarding static bones is displayed on traffic lights whilst the ranges of motion of dynamic bones are displayed on dials. The user can see the video recording of the demonstration and his own skeleton as tracked by the Kinect with each bone in a different color depending on its score" as shown in Figure 2.7.

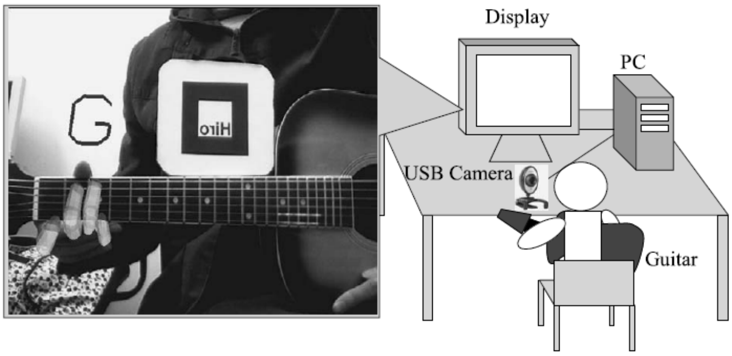


Figure 2.8: Proposed system for supporting playing a guitar (Motokawa and Saito [2006])

Figure 2.9: 3D arrow to guide user's movement in Light-Guide (Sodhi et al. [2012])

Guidance using novel methods for the delivery of feedback

Studies within the HCI community has also focused on movement guidance using novel methods for the delivery of feedback. Motokawa and Saito [2006] proposes a system using augmented reality to teach how to learn to play the guitar. The developed system as shown in Figure 2.8, uses a square shaped planar marker and the guitar's natural features to track the pose and position of the guitar. The tracking is achieved via a USB camera, which captures the user's images; these images are used to estimate the pose and position of the guitar using the AR toolkit and edge based tracking algorithm. The final output is provided on a PC display in the form of an overlaid virtual hand to guide the user with regard to his hand movements. Another study — Weing et al. [2013] describes the P.I.A.N.O. system for users who are beginners and wish to learn to play the piano. The system provides feedback and feed-forward using light cues which are projected onto the piano keys using a DLP projector and a display attached to the keyboard. The light cues are color coded and differ in size to allow for finger switches and overview of upcoming notes. The preliminary evaluation in this study didn't involve judging how well or fast the user has learned the song, rather it was aimed at understanding whether the fingering information is enough and what visual scope is used by the user. LightGuide (Sodhi et al. [2012]) used on-body projections to guide a user's hand through 3D space, one of which is shown in Figure 2.9. The hand is tracked using a Microsoft Kinect Depth Camera by determining regions of continuous depth after removal of redundant objects from the scene. A wide angle projector aligned with the camera is used to project the hints in 1D, 2D and 3D designed to provide feedback and feed-forward information to the user.

Need for digitizing skill

Due to technological advancement the research in the field of motor training and feedback is gaining interest. Nonetheless, most of these systems still rely on human involvement to provide feedback, for instance Chinthammit et al. [2014] provides an effective method of delivering instructions but remotely. Some systems provide the method of extracting expert information as in Velloso et al. [2013], but they don't address learning or explore the best way of providing feedback. Also, some of the systems provide feedback in a manner which is not sufficient for technical gestures. For example, Motokawa and Saito [2006] provides visual guide from the front angle instead of multiple angles which is not enough. Another example in this regard is Sodhi et al. [2012], in which feedback is only available for a single hand. Furthermore the feedback is only given when the hand is visible from the depth camera. Thus, there is need to digitize the skill and develop an evaluation model that depicts the most important features in the movements of the skill in order to provide rich feedback. We draw on the design decisions made by the different studies and chalk out the desired performance criteria and dimension space.

Chapter 3

Taxonomy and Dimension Space

In Chapter 2 "Related work", we described the feedback techniques which have been implemented so far. However, to arrive at a point where we can present the dimensions of feedback we need to discuss about some concepts. Fundamentals regarding different kinds of skills will help us understand how a skill may be categorized and exploring about feedback and movement patterns will enable us to determine what kind of technique could be employed for conveying movements for a skill. Once we have explored these properties, we will proceed to define the taxonomy related to our dimensions which explains the feedback requirements during skill movement acquisition. The proposed dimension space will be introduced after this based on the explained taxonomy

3.1 Background

3.1.1 Understanding skills

Skill classification

We have already introduced that educational activities which lead to the development of skills can fall under three major spheres Anderson et al. [2001] in 1 “Introduction”. These are further described below.

- Cognitive - This domain has to do with the development of a person’s intellect and knowledge.
- Affective - This domain deals with the development of an individual’s emotional quotient - a person’s attitude, gratitude and other feelings.
- Psycho-motor - This domain is concerned with physical movement, coordination and use of the motor-skill areas. Development in this domain requires training and practice, and can be measured with criterion such as speed and precision.

Compilation of psycho-motor domain model

Commonly these domains are referred to as Knowledge, Attitude and Skills by trainers. Several compilations of the psycho-motor domain model, have been suggested over the years Harrow [1972], Ej [1966], Anderson et al. [2001], which divide the domain further to describe the simplest to the most complex behavior. One popular compilation Armstrong et al. [1970], that fits our point of view, is described below.

- Imitation - This is absolutely the initial phase where the learner observes someone’s actions and movements and attempts to copy them.
- Manipulation - This is the phase in which the learner is able to perform the required movement for a skill by following instructions and practicing.
- Precision - In this phase the learner’s movements become more accurate and the number of errors are reduced to a great extent.
- Articulation - When this phase has been reached, the learner can co-ordinate a series of actions and related movements and perform with consistency.
- Naturalization - In this final phase, the learner can deliver a high-quality performance naturally, without having to think or remember about the movements of the skill.

In other words, what is required to perfect a skill is repetition. Research Grafton et al. [1992] has demonstrated that learning can occur from repetition which is supported by correct feedback. The recurring sensory signals from the moving limbs as they interact with the tools in the environment can finally lead to learning that particular movement sequence. This is because, although initially the movements are imprecise, the practice leads to the development of an internal model which can converge to the correct solution given proper feedback.

Repetition and imitation leads to learning

Now having understood how psycho-motor skills may be developed, we must delve into the domain of motor skills and understand its categorization. Motor skills has been classified into several categories based on the precision of the movement, the environment in which the movement takes place and the type of beginning or end a movement has by may researchers Davis et al. [2000], Galligan et al. [2002], Knapp [1963].

From the perspective of our system we are interested in skills which satisfy the following scope:

Scope of skills in our thesis

- Fine Skill - intricate precise movements using small muscle groups are required and generally the skill involves high levels of hand-eye coordination.
- Closed Skill - skill's movements take place in a stable, predictable environment and the performer knows exactly what to do and when.
- Internally paced Skill - the rate at which the skill is performed is controlled by the performer.
- Discrete Skill - the skill has a clear beginning and end.
- Individual Skill - the skill is performed in isolation, that is, the skill is not an interactive or co-active activity.

The most common examples of the skills that fall under the scope described above are playing musical instruments, knife skills, communication using sign language, conducting an orchestra and juggling.

3.1.2 Understanding feedback

Feedback classification

Feedback is defined as the information that the user receives about his actions during or after the movement has been performed.The feedback Smith and Lee [1998], Davis et al. [1991] can either be a natural outcome of performing any movement (called as inherent or intrinsic feedback) or feedback can be provided by an external source such that it supplements the intrinsic feedback (called as augmented or task extrinsic feedback).

Inherent or task-intrinsic feedback can be further categorized as follows.

- Exteroceptive - this is the feedback received by the user via observation of movements of objects in the environment or sometimes even self-reflection.
- Proprioceptive - this is the feedback that the user receives via his senses, in other words the feel of the movement that the user can perceive via his body signals, limb movements and joint angles.

Depending on the nature and source of inherent feedback, the performer can understand whether he has made a mistake or not. However, a reference of correctness is necessary in the mind model, which is usually not developed accurately until the late stages of learning. Therefore, inherent feedback can not be used to detect errors.

Dimensions of augmented feedback

Augmented or task-extrinsic feedback can have several dimensions as described below.

- Concurrent - this kind of augmented feedback is supplied during the performance of the movement.
- Terminal - this kind of augmented feedback is provided only after the completion of the performance of the movement sequences.
- Immediate - this kind of augmented feedback is delivered immediately after the performance.

- Delayed - this kind of augmented feedback is delivered after some amount of time has passed after the performance.
- Verbal - this is the kind of augmented feedback which is presented to the performer in a spoken form.
- Non-verbal - this is the kind of augmented feedback which is presented to the performer in a form which not speech.
- Accumulated - this is the kind of augmented feedback which is an aggregated feedback for the past few performances.
- Distinct - this is the kind of augmented feedback which is given for a specific performance.
- Knowledge of results (KR) - this feedback is about whether or not the user was able to achieve the target i.e. whether the user's performance was successful in relation to his goal.
- Knowledge of performance (KP) - this feedback is about the user's performance and technique. It is typically conveyed to performers by verbal cues, videos of the performance, pictures and other forms of visual data.

Studies Newell and Hancock [1981], Newell and Carlton [1987], Schmidt and Lee [1988] prove that for beginners trying to learn a complex skill it is better to provide KP. Given that the tasks which fall under our selected scope of skills can be considered as complex tasks, for this thesis we will concentrate on conveying KP feedback to our users.

3.1.3 Understanding human movement and its patterns

Reference positions and cardinal planes of movement

In order to obtain a proper description of human movement we need to define with reference to specific position or posture. Two positions as depicted in Figure 3.2 are defined – fundamental and anatomical. Furthermore, the movements

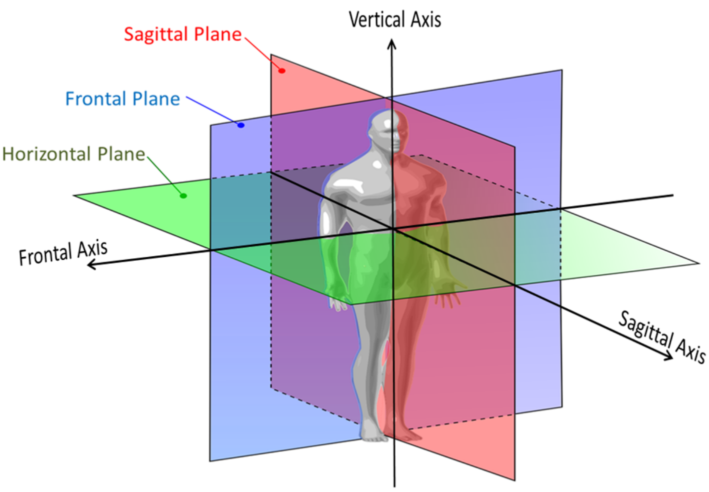


Figure 3.1: Cardinal planes of movement

can be said to be taking place along the cardinal planes – the sagittal, frontal and horizontal planes Bartlett [2007]. These planes are mutually perpendicular intersecting planes and the intersection of pairs of planes gives us three axes known as - the sagittal, frontal and vertical (longitudinal) axes. From these planes and axes are shown in Figure 3.1, we understand that exercise movements such as running takes place in the sagittal plane, and movements related to say, chopping of vegetables takes place in the frontal plane. As discussed before skills and activities such as playing an instrument falls under the scope of skills that we have chosen. Consider the skill of playing a piano - this skill links the natural hand and finger movements in a complex and well-codified pattern. So, to understand how to provide feedback for the movement patterns which fall under our selected scope we need to gain some basic insight about dexterity.

Human dextrity and Manipulation Taxonomy

Dexterity can be defined as the skillful manipulation involving one or more hands Wiesendanger and Serrien [2001]. Grasping and bimanual coordination form the core of dexterity. Several studies Bullock et al. [2013], Weber et al. have researched about dexterous manipulation for the purpose of developing a framework which can be applied to robot hand engineering. As mentioned in Bullock

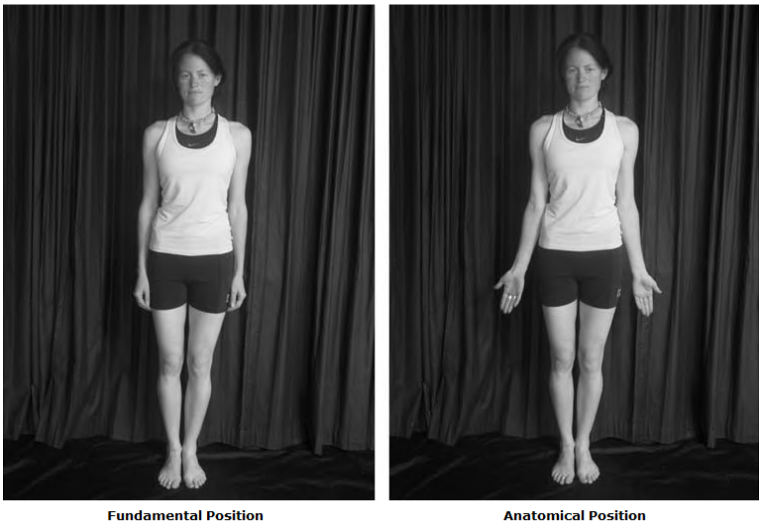


Figure 3.2: Reference positions (Bartlett [2007])

et al. [2013], while interacting with an external object, the following elements are important.

- Contact - hand touches the external object or the environment.
- Prehensile - action requires more than one finger.
- Motion - any joint in the hand moves relative to a specific body frame.
- Within Hand - fingers move relative to a specific hand frame.
- Motion at Contact - touch to the object moves relative to contain point frames.

Based on these elements a taxonomy of manipulation has been defined as shown in Figure 3.3. Using this taxonomy we can define what category a particular movement will fall under and subsequently analyze the strategy to evaluate the manipulation.

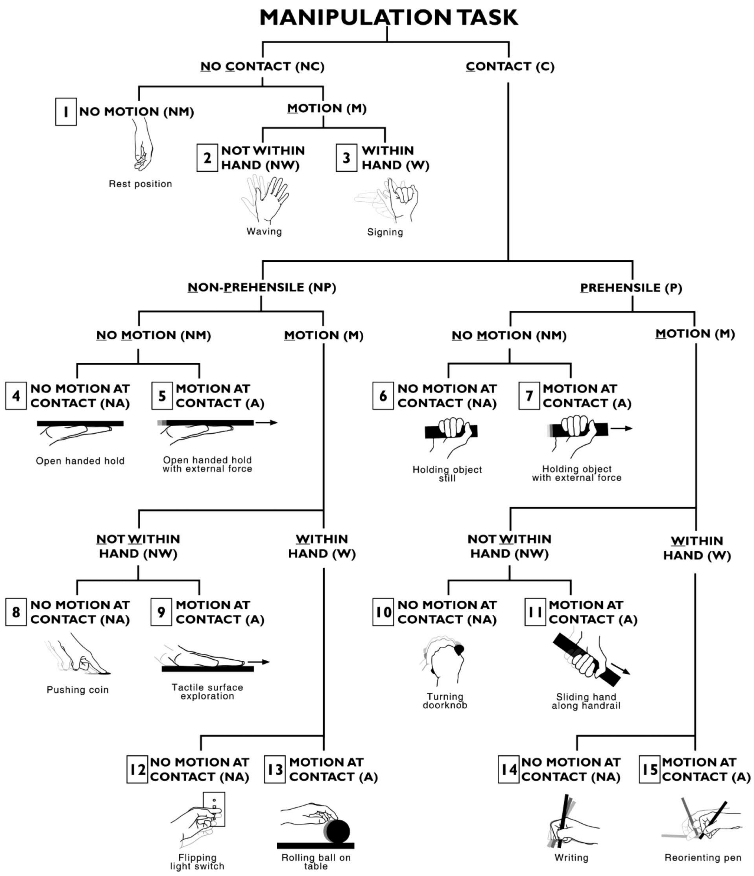


Figure 3.3: Manipulation Taxonomy (Bullock et al. [2013])

3.2 Dimension Space

Design space analysis

The concept of design space analysis was introduced in MacLean et al. [1989] as part of a framework meant to represent design decisions for designed artifacts. Since then design space analysis has been used to usefully study and describe the overall structure in several domains such as augmented reality prototype for air traffic control (Mackay et al. [1998]), adaptive graphical user interfaces (Gajos et al. [2006]) and interactive public displays (Müller et al. [2010]).

The construction of design space of a system leads to the identification of a set of key functional and structural possibilities (Questions) while creating the system and also the choices available for each possibility (Options). In addition to these possibilities and choices, rules (Criteria) which link different possibilities form an important part of the design space. Design space analysis exposes patterns among different dimensions and helps in designing an optimal system where the reason behind every choice is clear and understood.

Problem with design space analysis

However, design space analysis doesn't provide enough methodical support for design of systems which involve actors interacting with objects both in the physical and virtual worlds to complete a task. Since any system which intends to teach a skill has both virtual and physical entities, we will use the Dimension Space as described in Graham et al. [2000b] to elaborate about possible design choices.

3.2.1 Design Concerns

Static design concerns

We begin by understanding the static design concerns of our system.

- *Involved entities:* We must start by realizing what our system is composed of. The entities that make up a system aimed at providing feedback for learning a skill include the objects used to perform the skill (if any), the user of the system, the hardware for collecting the user's movement data and of course the visualization supplied to assist the user.
- *Usage of the entities:* As the next step it is important to understand and design how the software entities interact with the physical objects, in other words what algorithms are at work behind the scenes. These algorithms determine the information type and content of the visualization. In the systems we have reviewed thus far, varying algorithms have been used. Further we need to understand how the users fit into the interaction model and what kind of interaction techniques can be employed.
- *Tradeoffs among entities:* While some entities are fixed, others can be replaced. For instance, if we want to design for conveying movement skills for playing gui-

tar, the guitar is a fixed entity whereas other entities such as the hardware used to capture the movement data (such as Kinect or MoCap sensors) or the feedback visualization are changeable. We need to recognize the tradeoffs among the available choices of replaceable entities.

Runtime design concerns

Besides the static design concerns, we must consider the runtime issues of our system.

- *System use over time:* The characteristics certain entities is bound to changes over time. For example, after a certain number of trials the user can no longer be regarded as a beginner and therefore the characteristics of other entities, such as the feedback visualization, must evolve to accommodate this change.
- *Discontinuities:* There may be discontinuities in the interaction with the system, for example when real-time visualization is provided, the user's attention can be divided between a couple of entities. These need to be resolved to allow for smooth interaction experience.

3.2.2 Axes of Dimension Space

Defining Dimension Space axes for our thesis

As we have already discussed in 2 "Related work", the Dimension Space as originally proposed represents interactive systems on six axes. We have adapted the dimension space for conveying feedback for skill movement acquisition. In doing so we explored several values and configurations of axes based on knowledge gathered from the previous section 3.1 "Background". Descriptive detail of each of the six axes as depicted in Figure 3.4 is provided in the following points.

1. Feedback timing

   Concurrent

   Terminal

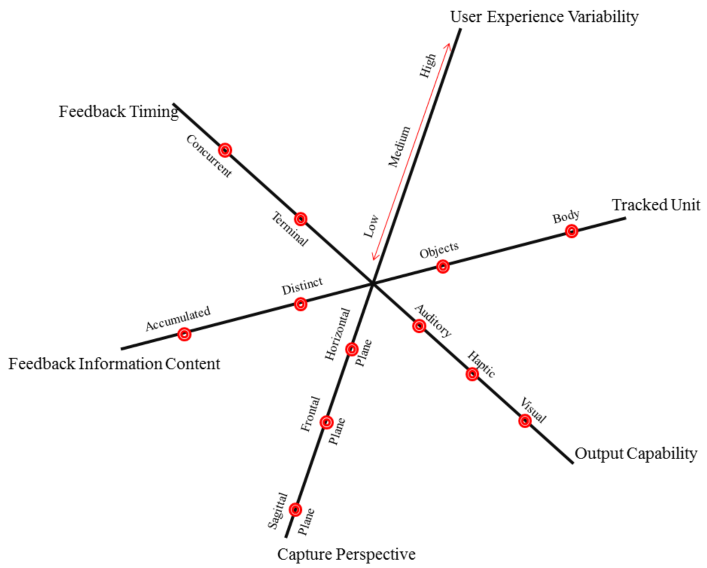


Figure 3.4: Dimension Space for conveying feedback for skill movement

Concurrent feedback means that the feedback will be delivered real-time, i.e. while the user is performing the action sequences. Many studies discussed in 2 "Related work" like Sodhi et al. [2012] provide concurrent feedback.

Terminal feedback indicates that the feedback is delivered after the user has finished the performance of the skill. Anderson et al. [2013] has the option to provide terminal feedback to the users at the end of their performance.

2. Feedback information content

   Accumulated

   Distinct

   Accumulated feedback is a way to provide feedback about multiple performance, in other words, it provides averages of selected performances. While in distinct feedback, feedback is provided for a specific movement. For instance, the feedback information provided by the Performance interface in Velloso et al. [2013] is discrete in nature.

3. Capture perspective

   Sagittal plane

   Frontal plane

   Horizontal plane

   As discussed in 3.1.3 "Understanding human movement and its patterns" human movements take place along specific cardinal planes. In layman terms sagittal plane perspective is equivalent to side-view capture, fontal plane perspective is equivalent to front-view capture and horizontal plane perspective is equivalent to top-view capture. Data for providing feedback must first be captured along the primary plane in which the task is being performed as long as it is unhindered by the manipulated object(s).

4. Output capability

   Auditory

   Haptic

   Visual

   After review of current methods, we understand that there are four possible modes of delivering feedback.

   Feedback could be audio which qualitatively or quantitatively conveys the review of the user's performance. Haptic feedback can be used for tasks which involve object manipulation either when a user has performed the correct action or when he has not. Visual feedback can range from very low fidelity such as text to a graph constructed from user's movement data. Feedback mode could be such that its reality is blended in with virtual images, i.e. augmented reality. Anderson et al. [2013], Mitobe et al. [2012] can be considered as two examples of systems which provide augmented reality feedback.

5. User experience variability

   High

   Medium

   Low

   System could be catered to providing variability in feedback provided depending on user's experience. High variability would indicate different feedback is provided for novice and experienced users, medium would indicate that minor changes in the feedback are made available for the experienced users and low would indicate that the system doesn't adapt to different experience levels of users.

6. Tracked unit

   Objects

   Body

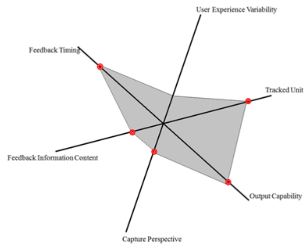
   This dimension addresses the last and most important task of a feedback system, which is tracking an object with the view of collecting information for providing feedback to enable the user reach his performance goal.

   Some tasks require the manipulation of external objects, for example, sharpening a knife. For these tasks, feedback would be incomplete without collecting and presenting data regarding manipulated object.

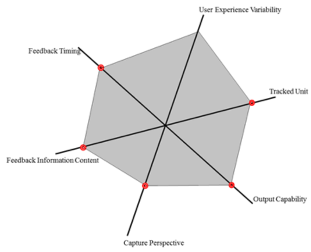
   In other tasks objects are absent, for example, communicating using sign language. For such tasks the appropriate part of the human body must be tracked to provide feedback.

Dimension Space plots for systems in Related Work

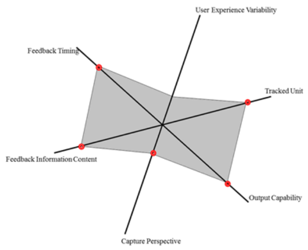
We can use these axes to construct plots, which will help us in contrasting the choices and examine different design options. Figure 3.5 shows dimension space plots for the



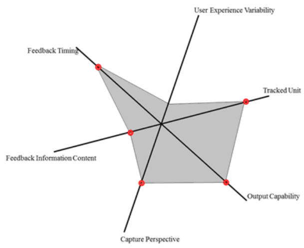
Ubiquitous Tenalai-docolo (Mitobe et al. [2012])



YouMove (Anderson et al. [2013])



LightGuide (Sodhi et al. [2012])



Physio@Home (Tang et al. [2015])

Figure 3.5: Dimension Space Plots

feedback provided by Ubiquitous Tenalai-docolo (Mitobe et al. [2012]), YouMove (Anderson et al. [2013]), LightGuide (Sodhi et al. [2012]) and Physio@Home (Tang et al. [2015]).

Chapter 4

Performance Measurement Criteria and Visualization

4.1 Performance Measurement Criteria

Need to capture skill data to define performance measurement criteria

To design a visual feedback which is rich in information and a good representation of all the critical features, we need to define a performance measurement criteria for the skill under study. For arriving at this evaluation measure we need to understand, capture and analyze the characteristics that define a unique skill.

Reasons for choosing knife honing

For the purpose of this thesis we wanted to choose a skill with few key gestures which had a repetitive rhythm and could be learned in a short while. We went through several videos and web-blogs about activities such as learning to play the piano (Palmer et al. [1982]), learning to play the guitar (Manus and Manus [1992], Duncan), rehabilitation (Glynn and Fiddler [2009]), yoga (Mittra [2002], Long and Macivor [2009]), juggling (Beek and Lewbel [1995]), dance practices (Carroll and Carroll [2012]), card tricks (Longe [1993]) and knife skills (Hertzmann [2007], Rama and Miller [2014], Jay and Fink [2008]). Ultimately, we chose knife honing as the skill to be learned. Honing a knife

Figure 4.1: Tools used for our knife honing task – Ceramic honing rod and Kitchen knife

realigns the edge of the knife which consequently sharpens a dull knife (Jay and Fink [2008]). Most chefs hone their knives before every use and this task can be performed with a rod of steel, ceramic or diamond coated steel. The skill involves running the blade of the knife at an approximate angle along the honing rod in an arcing motion, and must be repeated few times until the edge realigns. The tools used to perform the task in our data collection procedure are shown in Figure 4.1.

Capturing skill using Vicon Nexus

We chose to capture the skill using an infrared tracking system — Vicon Nexus, because of its ability to capture the skill from multiple angles. As understood from Chapter 2 "Related work", capturing data from multiple angles will give us information to show feedback from all required positions. Further, Vicon Nexus' performance, high resolution and sampling rate give it an edge compared to other human motion capture tools (Pfister et al. [2014]).

4.1.1 Understanding skill characteristics

Common errors in knife honing

In order to understand the characteristics of knife honing we went through videos available on the internet and spoke to a chef who has been trained in knife honing. From the available literature and discussions with expert, it was determined that any novice user can make the following errors during knife honing.

- The angle between the honing rod and the knife is not in the range of 12-20 degrees.
- The honing rod is not held straight but inclined at an angle throughout the knife honing action.
- The honing rod is not held stably and it wobbles while the user performs the stroke with the knife.
- The user doesn't sharpen the entire range of the knife's blade from the base to the hilt.

Capturing expert data as baseline skill model

In addition to the discussions, we decided to capture the expert performing the task. The reason behind this decision is two-fold – firstly, research (Wood [2009]) has already shown that there is a difference in the way an expert demonstrates his movements and the way he talks about them; secondly, capturing the expert's movements allowed us to experiment with the position of markers on the objects used in the skill, which will be tracked by Vicon Nexus.

Placing markers on objects

Based on our observations and our understanding of human movement patterns in 3.1.3 "Understanding human movement and its patterns", we can categorize knife honing as C P M NW NA, and this communicates that the knife is grasped in the hand, fingers don't move relative to the hand frame and the hand and the knife moves as a whole; from this we can conclude that we could capture motion data of the object alone. Thus, we placed the reflective markers on the honing rod as shown in Figure 4.3, and on the knife as shown in Figure 4.2. The arrangement of the markers on the knife is identical on both sides, however we can distinguish the side of the stroke based on the 3D data collected. The markers on the honing rod are placed on the handle, so that it doesn't interfere with the activity of knife honing.

4.1.2 Skill Capture

To decide on the performance measurement criteria we not only captured data from the expert performing the skill but also from novice users. This helped us determine which

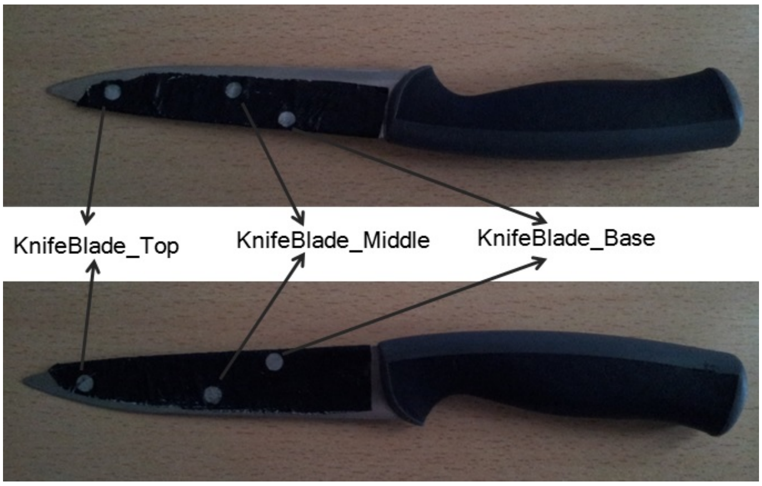


Figure 4.2: Reflective markers placed on both sides of the knife

Figure 4.3: Reflective markers placed on the handle of the honing rod

of the common mistakes we should focus on and how to mathematically judge the error made.

Vicon Nexus setup

Our motion capture setup included the Vicon Nexus system consisting of 8 Vicon Bonita cameras operating at 100 Hz, mounted on tripods and camera mounts, focused at the table where the motion capture activity took place as can be seen in Figure 4.4. This viewable area is called as the capture volume.

As mentioned before Vicon Nexus tracks motion using markers. These reflective markers are made out of special retroeflective tape. The Vicon Bonita cameras are standard digital cameras which are surrounded by a ring of LEDs. The infrared light emitted by these LEDs is reflected by the markers and detected by the cameras. Since the light

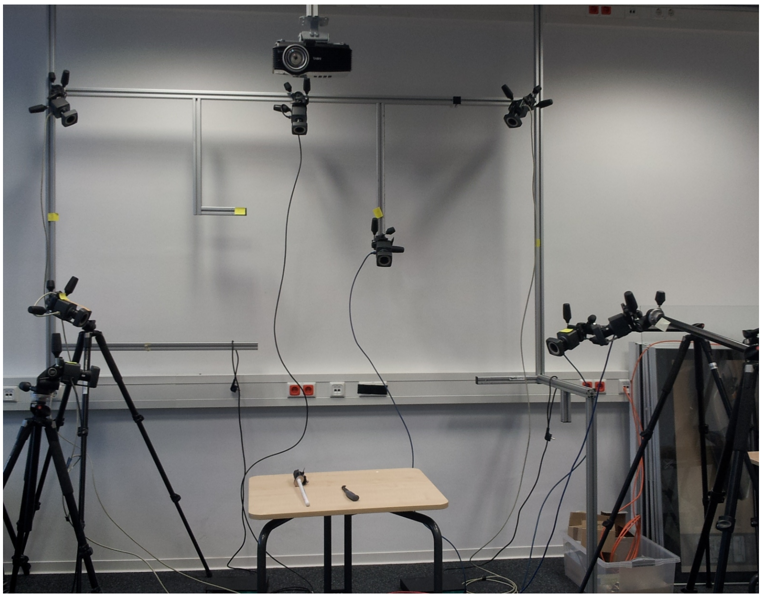


Figure 4.4: Vicon Bonita camera setup directed towards capture volume

that bounces off retroeflective tape is much more than other surfaces, the camera system manages to efficiently differentiate between markers and other reflecting objects. Further, for the accurate reconstruction of the 3D coordinates of the marker, Vicon Nexus demands that the marker be visible by at least 2 cameras. Having fixed the markers as discussed in the previous subsection 4.1.1 “Understanding skill characteristics”, we proceeded to prepare the system and subject for motion capture. During data collection process we wanted that the origin remain unchanged and the users place the honing rod at the origin. To help achieve this goal we marked a box on the table with tape and as the final step of system preparation we set the volume origin by placing the wand in the marked box. As part of subject preparation, we created Vicon Skeleton (.vsk) file for both the knife and honing rod to be used for each capture session. After this we conducted pilot session as described in the following subsection.

Pilot data collection session

The purpose of the pilot study was to verify camera configuration

Before going ahead with the main data collection session to evaluate the correctness of our marker placement and overall procedure, we carried out a pilot data collection session. The purpose of the user study was to find out whether the current camera configuration yielded accurate results for the way the novice users would handle the tools of the task. So, if the results were not as expected, the camera arrangement would need to be changed. We conducted the study with a setup similar to the pilot session. We recruited 2 participants (1 female and 1 male) for the pilot. Both the participants were right handed.

Pilot study and task description

Each user was shown a demonstration video (on a Mac Pro 22 inch display) with a focus on how the tools must be held and their purpose. The users then had to perform 3 trials, where each trial comprised of 10 strokes of knife honing; this was captured using Vicon Nexus. After every trial the user was shown the demonstration video again. During the study we recorded videos of the user's performance using a GoPro camera at 60fps. Later we analyzed the videos and the captured data to determine how correct the camera arrangement was and how often the users make the common mistakes.

Pilot study results

The analysis showed that the camera arrangement could successfully capture the user data accurately and the common mistakes identified were made by both users. Thus, these results permitted us to carry on with the collection of training data.

Participants

For the main data collection study we recruited a total of 12 participants (7 female and 5 male) – 11 novice users and 1 expert. The participants' age was in the range of 23 and 30 (average age 26). From the novice users 10 were right handed and 1 was left-handed, and the expert was right-handed. During the process, the participants were requested to use their dominant hand to hold the knife and the other hand to hold the honing rod. On an average the data collection required 0.5h per user.

Before beginning the data collection the participants were asked to answer the questions, from the data collection questionnaire (A "Background Information Questionnaire"), regarding their previous experience in knife honing/sharpening and knife skills. After the first trial the participants were told about the possible mistakes they could make and were asked to explain about the mistakes they thought they had made (B "Data Collection Questionnaire"). The questions were posed to the participants and the answers given were noted. 3 among the novice users had previous sharpening knives with stones, 1 had some experience sharpening knives using honing rod, while the remaining 7 had no experience at all in knife sharpening/honing.

General procedure

The general procedure of data collection was similar to the procedure followed during the pilot with the addition of questionnaires. Also, before starting, the users were given an opportunity to familiarize themselves with the tools of the experiment to allow any correction in the way the tools were held.

Post-processing of data

Reconstructing lost data in Vicon Nexus

The trials capture in Vicon Nexus were reconstructed using the Label and Reconstruct pipeline. In general there are five types of data issues which can be observed after reconstruction as listed below.

- Markers may disappear for some milliseconds
- Markers lose their label and then become labeled again
- After reappearing, the marker is wrongly labeled

- Markers disappear and appear, however remain unlabeled
- Markers position is not constant and it flashes erratically.

For majority of the users the number of gaps or missing markers was minimal. The reason for difference in data quality from one capture to another can possibly be attributed speed of the user's knife movement. We addressed the data issues by either labeling missing data manually or conducting gap filling using internal algorithms of spline fill or pattern fill.

After completing the reconstruction successfully, the data was annotated to indicate the start (Foot Off) and end (Foot Strike) of every stroke. The time bar in Vicon Nexus allowed us to mark the left and right strokes distinctly.

Reviewing captured videos

Additionally, the videos of the participants were reviewed, by the expert and us, to indicate the errors made (C "Stroke Performance Table")

Discussion

Novice user can't make out mistake made. Hence, great need for feedback

The participants were comfortable using the tools and the way the markers were placed didn't interfere with their performance. We asked the participants to explain the mistakes they had made after each trial; the reported answers more often than not didn't match the mistakes that the expert observed from the performance videos. However, the mistakes indicated by the expert from the video review were quite consistent with the mistakes determined from the mathematical analysis of the collected 3D data. Thus, we can deduce that a novice user is not able to understand whether he has made a mistake, even though the different kinds of mistakes have been described to him in detail. Furthermore, our analysis and review revealed that the errors commonly made by the users are those of knife/honing rod angle and honing rod stability. Therefore, as part of our fi-

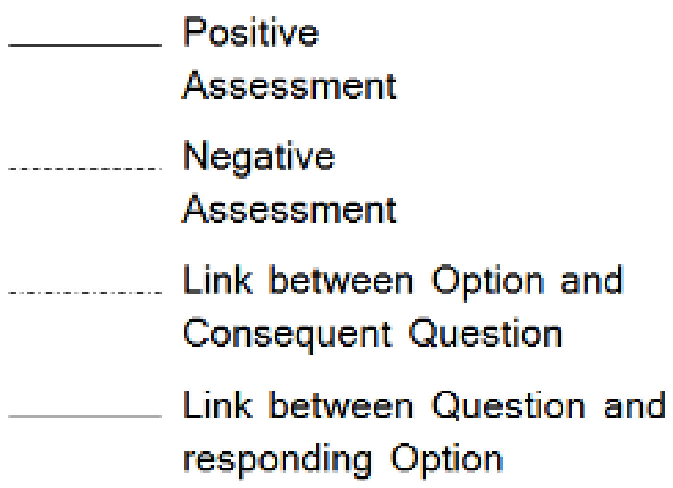


Figure 4.5: Notations used in QOC (MacLean et al. [1991])

nal evaluation we decided to design visualizations specifically for these two mistakes.

4.2 Feedback visualizations

We designed feedback visualizations to transform the data from user's movements into a perceptually efficient visual format based on our Dimension Space, so that the users could view their errors along with the correct movements from the expert.

4.2.1 Rationale

Although the Dimension Space doesn't explicit include the QOC (Questions-Options-Criteria) method from the Design Space Analysis paradigm, we will use it to provide justification for the choices in our feedback visualization. The notations we have employed by carrying out the QOC method are depicted in Figure 4.5. Most of the questions and options are based on the dimensions as defined in 3.2.2

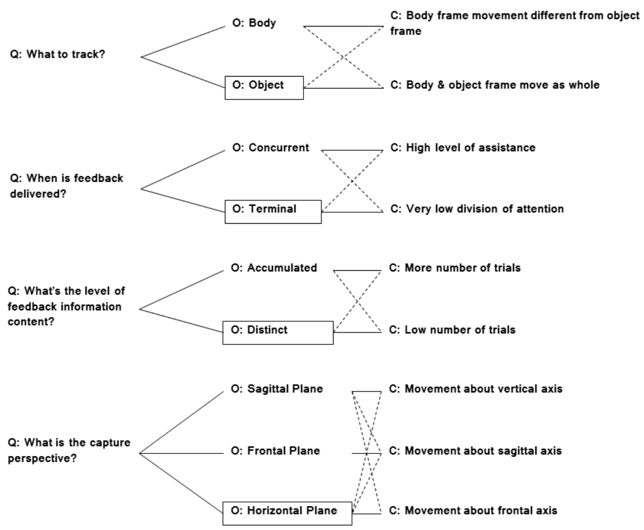


Figure 4.6: QOC analysis of Dimension Space - Part 1

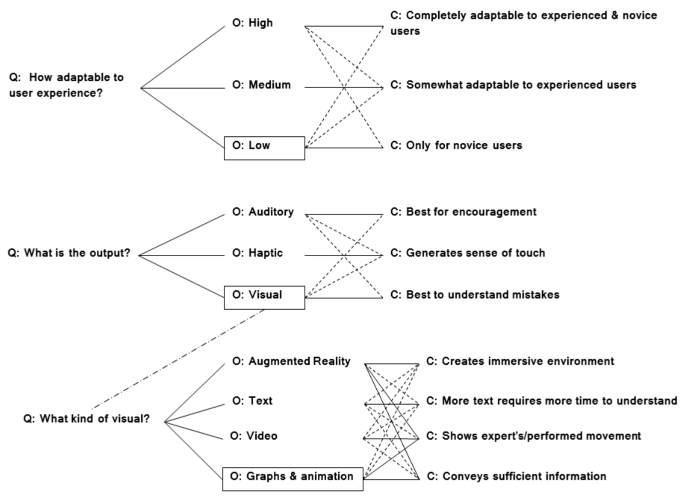


Figure 4.7: QOC analysis of Dimension Space - Part 2

"Axes of Dimension Space". These are depicted in 4.6 and 4.7.

For knife honing, objects should be tracked

The first question we can pose is *What is tracked?*. We consider Body and Object as two options. The criteria *Body frame movement different from object frame* and *Body & object frame move as whole* are derived from the principles discussed in 3.1.3 "Understanding human movement and its patterns". It basically claims that if the movement of the hand and the object do not differ then we could only track the object to generate data to provide feedback, whereas if the hand movement differs from the object movement we would need to track the body part involved in the movement. Therefore, in the case of knife honing, as explained in 4.1.1 "Understanding skill characteristics", we choose to track the objects that are the honing rod and the knife.

Terminal feedback is better for long term retention

For the question *When is feedback delivered?*, the criteria *High level of assistance* and *Very low division of attention* are based on research done in the field of motor learning and human computer interaction to compare the Options – Concurrent and Terminal feedback. Concurrent feedback seems to be the common choice for providing guidance as can be seen in the studies reviewed in 2 "Related work". It indicates the nature and the direction of the movement for required corrections needed. However, studies (Sigrist et al. [2013], Schmidt and Wulf [1997], Alikhan et al. [2011]) prove that concurrent feedback facilitates the correct performance briefly but it proves to be a great source of motivation for the users. Also, concurrent feedback can cause interactional discontinuity because the user may be forced to divide his attention between the guidance and the actual performance. Terminal feedback, on the other hand, avoids the interactional discontinuity altogether because the feedback is provided once the user has finished the task performance. Further, terminal feedback is said to change the cognitive processes involved in motor learning thereby allowing for more effective learning. We chose to provide terminal feedback due to the above mentioned advantages of the same.

Distinct feedback chosen for feedback visualization

The next question *What's the level of feedback information content?* has the criteria *More number of trials* and *Less number of trials* for its options Accumulated and Distinct respectively. Although Schmidt [1991] shows that accumulated feedback may be used to show the user the common systemic errors made over time, it also indicates that distinct feedback can help to provide independent feedback about each discrete action. Consequently, to provide accumulated feedback we need to collect more data for which more trials are required, while for distinct feedback the feedback information can be derived from few trials. Due to time restrictions we have chosen to opt for Distinct feedback.

Knife honing must be captured from horizontal plane

The criteria for the next question *What is the capture perspective?* is obvious and it is dependent on the axis about which the user performs the movements as discussed in 3.1.3 "Understanding human movement and its patterns". Since we have chosen the task of knife honing we need to capture from the horizontal plane perspective.

Low adaptability used for feedback visualizations

The subsequent question is *How adaptable to user experience?*, for which the criteria vary among *Completely adaptable to experienced & novice users*, *Somewhat adaptable to experienced users* and *Only for novice users*. These criteria are based on the research (Newell [1991]) which explains that the level of skill increases with practice over time and eventually the kind of feedback requires changes. At the nascent stage, the user needs a very descriptive feedback because the mental model for the task movements is in the process of formation. But as the user practices and become more proficient in the task, less descriptive feedback can help his performance. For our visualizations we have chosen to design only for novice users because time restrictions would not allow us to evaluate any visualizations designed for intermediate or experienced users.

Visual feedback provides highest information content

The final question is *What is the output?* which relates to how the feedback is presented to the user. The criteria is established on the characteristics of the different modes that may be employed for providing feedback. Investigations (Avanzini et al. [2009]) regarding the role of auditory feedback in motor learning show that it proves to be very useful in engaging the user in the task and providing encouragement. Weiss et al. [2014] elaborates that "Haptic feedback can be used to add the perception of contact" during the performance of the skill, whereas visual feedback gives us highest amount of information to understand the mechanism of error-correction; therefore we chose to design for providing visual feedback. However, we need to explore

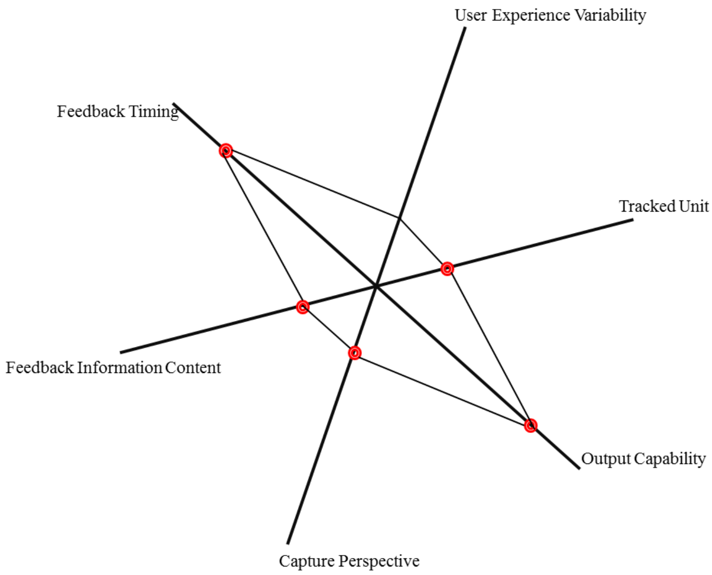


Figure 4.8: Dimension Space for our Feedback Visualizations

and precisely choose the kind of visual feedback to provide. Again, the criteria is derived from the features of the different kinds of visual feedback. We have chosen the option of graphs and animation because it can convey sufficient information and is quick in terms of development time. Thus, our choices can be represented in a Dimension Space plot as shown in Figure 4.8.

4.2.2 Implementation details

Visualizations designed using Python as 3D graphs

We implemented a program in Python 2.7[1] to be executed in a supervised fashion, to generate the visualizations. The real time data from the user's performance was captured using a simple Python library for retrieving data from a Vicon motion capture system called pyvicon [2]. The Matplotlib 1.4.3 library[3] , which is a portable Python plotting

[1]http://www.python.org
[2]https://github.com/cfinucane/pyvicon.git
[3]http://matplotlib.org

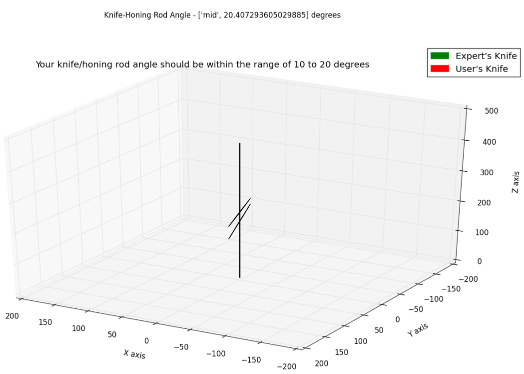


Figure 4.9: Honing rod and knife angle visualization

package along with Scipy library[4] of scientific tools, were used to find the peaks and troughs from the collected data. One cycle of peak to trough represents one stroke of knife honing. Data from first cycle was used to calculate honing rod and knife angle and honing rod jitter and shown to the user as two separate visualizations to reduce the user's cognitive load.

Constructing angle visualization

For the first visualization regarding the angle, the length of the honing rod was divided into three ranges and the angle between the honing rod and knife was calculated at the highest point in each range. The resulting computations were compared to the expert's computations arrived at in a similar manner. To represent the comparison between the expert's and the user's angle, we plotted the surface containing the markers of the knife in a 3D graph as can be seen in Figure 4.9. The final visualization is shown as an animation which shows the angles one by one in the three ranges.

Constructing jitter visualization

In the second visualization for calculating the jitter, we established threshold values in 3D space from the expert's data and checked whether the honing rod markers' coordinates lay within the threshold range. If yes, it was drawn in a 3D graph as an animated line in blue, else it was rendered in red. The expert's honing rod was drawn as a static

[4] http://www.scipy.org/

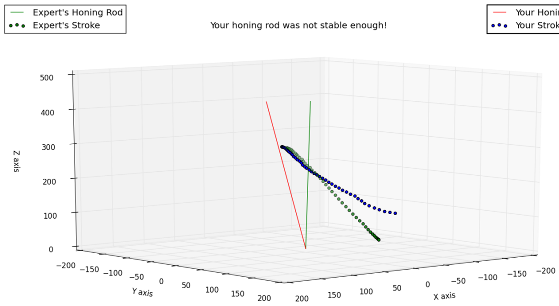


Figure 4.10: Honing rod jitter and stroke trace visualization

line. In addition to programming for these errors in this visualization, we added the stroke trace of the expert in green and showed the user's stroke in blue to give a rough idea as to how the ideal stroke pattern would look like as shown in Figure 4.10.

4.3 Preliminary Study

We conducted a preliminary study with 10 participants (2 female and 7 male) to confirm whether the view point selection of the 3D graph conveyed enough information to the users to understand their mistakes and to ensure that the procedure we intended to follow during the full-scale study was unambiguous. The participants had little to no experience in sharpening/honing knives.

Prelimnary study needed to confirm view point of 3D graph

We ran the study with a setup similar to the pilot for the data collection session (4.1.2 "Pilot data collection session"), and maintained the elements we had decided upon during the data collection process – Vicon Nexus motion detection with 8 Vicon Bonita cameras, marking the center on the table where the honing rod needed to be placed and 22 inch Mac Pro display to show the demonstration video and the feedback visualizations to the users.

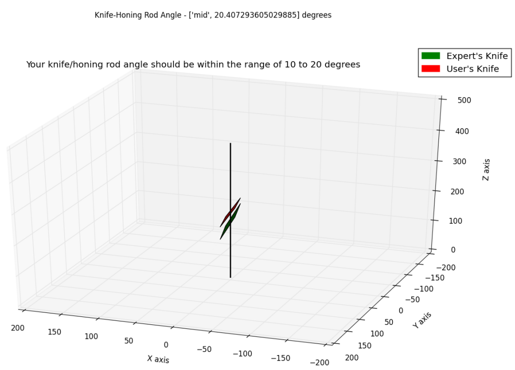


Figure 4.11: Modified honing rod and knife angle visualization

General procedure of prelimnary study

Users were asked to view the demonstration video and then perform the knife honing task (10 strokes/5 strokes on either side) with the tools kept in front of them. After their performance was over they were shown the feedback visualizations one after the other on the screen in front of them. The entire study was video recorded and before moving on to the next knife honing trial, the users were asked to report what they understood from the visualizations. Each user performed 4 knife honing trials in total. After the performance, we allowed the user to interact with the 3D graph and indicate if they found another view point to be more useful in conveying their mistakes.

Results of prelimnary study

The results helped us adjust the azimuth and elevation of the 3D graph as shown in Figure 4.11 and Figure 4.12. Having achieved the purpose of the preliminary study we continued with the main user study.

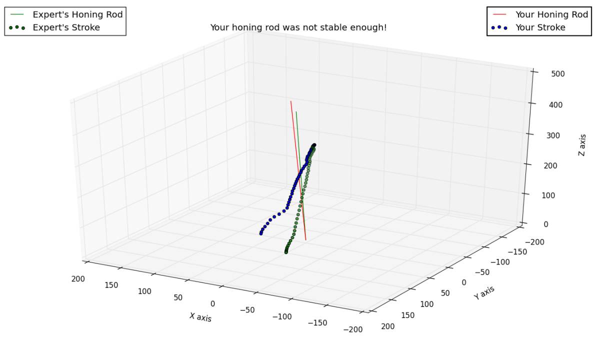


Figure 4.12: Modified honing rod jitter and stroke trace visualization

Chapter 5

User study

We performed an experiment to evaluate our visualization's efficiency (in terms of improvement time) and effectiveness (in terms of better fitting to the expert performance model).

The purpose of our study is evaluate designed feedback visualizations

The independent variables for our experiment were defined as follows.

Independent variables of our experiment

1. Feedback Type: This independent variable indicates the type of feedback which is provided to the users after their performance. Its scale is Nominal and it has two levels as listed below.
   - Visualization: The designed visualizations with abstract meta-data showing animated expert skill execution along with the user's meta-data.
   - Video: The video composed of expert's actions showing a particular movement pattern.
2. Trial: This independent variable indicates the successive trials of the task performed by the user. Its scale is ordinal and it has 4 levels for 4 trials — t1, t2, t3 and t4.

The dependent variables were derived from mistakes iden-

Dependent variables of our experiment

tified when conducting the pilot for the data collection session (4.1.2 “Pilot data collection session”). For our experiment we defined them as follows.

1. Angle: This is the first impact angle between the knife and honing rod, which is measured and reported in degrees. It used to determine whether the impact angle of the user is in the range of 10 to 20 degrees.

2. Jitter: This is the difference between the maximum deviation between the expert’s honing rod and the user’s honing rod in all dimensions. It indicates the stability of the honing rod as compared to the expert’s and is measured in mm.

Our hypotheses

Before the experiment we hypothesized the following outcome:

- **H1:** The feedback type has a significant influence on the angle and jitter (in all dimensions).
- **H2:** The feedback type and number of trials interact to influence the angle and jitter (in all dimensions).

5.1 Task

Knife honing task with ten strokes

The participants were asked to perform the task of knife honing. They were requested to remove any jewelry or metallic accessories to allow for better Vicon Nexus accuracy. Then, the participants were asked to watch the demonstration video. We had decided to recruit only right-handed participants for the experiment. So after the demonstration video, every participant was asked to hold the knife in his right hand and the honing rod with his left hand. Further, he was requested to hold the honing rod at the marked box on the table which indicated the origin of the 3D coordinate system of the Vicon Nexus. Following this they were told to perform 1 trial (10 strokes) of knife honing starting from the right side. After the trial they were shown appropriate feedback. The process of performing trial and viewing the feedback was repeated 3 more times. It was emphasized that the participants should try to correct their mistakes rather than perform the action more quickly.

5.2 Pilot study

Before conducting the main user study, we conducted a pilot user study to make sure that the general procedure and task was well-defined and not tiring to the users. We ran the study with a setup same as the one from 4.3 "Preliminary Study".

Pilot study conducted to endure correctness of general procedure

We recruited 2 users (2 male). Both of them had no experience in honing/sharpening knives. Users were instructed to perform the knife honing task with 10 strokes as described in the previous section 5.1 "Task", and fill out questionnaires from A "Background Information Questionnaire", D "Error Visualization Trial Review Questionnaire" and E "Error Visualization System Post Performance Questionnaire" before, between the trials and after the entire experiment was done respectively. During the study we recorded the videos of users performing the task.

Pilot study procedure

From our analysis of the videos and questionnaire answers we concluded that the general procedure of the experiment and task were appropriately defined and didn't prove tiring to the user. Thus, we continued to conduct the final user study for this work. The setup as described 5.2 "Pilot study" was used for the final experiment.

Results of pilot study

5.3 Participants

A total of 9 participants (2 female and 7 male) aged between 23 and 29 (average age - 25) took part in our study. All the users were right handed. They were all requested to use their dominant hand for holding the knife and the other hand for holding the honing rod just as in the pilot session. The study took 0.5h to complete on an average.

General procedure followed during experiment

Before the viewing of the demonstration video we collected information from the users about their previous knowledge related to knife honing/sharpening and their knife skills (A "Background Information Questionnaire"). After every trial the users were asked to rate their understanding of the feedback for each mistake on a 5-point Likert scale (D "Error Visualization Trial Review Questionnaire") which ranged from strongly agree to strongly disagree. After the entire experiment was done, the users had to fill out a final questionnaire (E "Error Visualization System Post Performance Questionnaire") which was also based on a similar 5-point Likert scale. This questionnaire was meant for evaluating users' overall understanding, preference and confidence level. Of the 9 participants, 4 had no previous experience in honing a knife, 3 had some experience with the honing rod, while 2 were experienced in sharpening knives using stone.

5.4 Experimental Design

We used a Within-Subjects design for both independent variables – feedback and trial. Feedback was counterbalanced. We had four blocks of Trials, and for every trial we had 2 feedbacks. One feedback was paired with one feature, that is to say, we have one feedback for angle and another for jitter. So, we had 36 data points for each Dependent Variable (9 participants x 2 feedbacks x 4 trials = 36)

5.5 Results

Peaks and troughs used to identify strokes and calculate angle and jitter

We designed an algorithm to calculate the peaks and troughs, from the received data. This algorithm first found all the local maxima and minima in the z-axis data. These maxima and minima were then filtered by calculating high-

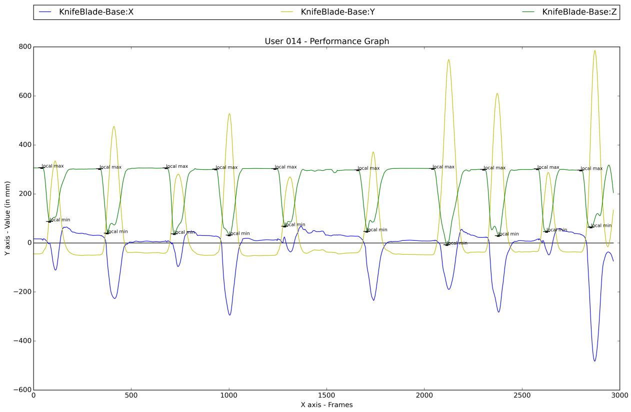


Figure 5.1: Performance Graph for User 1 - Trial 4

est peaks and troughs. Each consecutive pair of peak and trough then signified one stroke of knife honing. Our algorithm identified the first ten strokes from the received data as depicted in Figure 5.1. For each stroke we then calculated the first impact angle between the honing rod and knife at the peak point of every stroke. We also calculated the jitter (in all dimensions) for every frame of each stroke. For both angle and jitter (in all dimensions) for one stroke, we computed the median to be used in the final data analysis. Using median allowed the data to not be sensitive towards the outliers. The resulting data met with the main assumptions as listed below.

- Variance between groups (Visualization and Video) was homogeneous.
- Data was normally distributed.

Thus, it was analyzed using two-way ANOVA.

For the honing-rod knife impact angle the p-value (Feedback Type) = 0.1154 $\geq 0.05 = \alpha$. And, the values for p-value (Trial) = 0.6886 $\geq 0.05 = \alpha$, and p-value (interactions) = 0.4377 $\geq 0.05 = \alpha$. The results are as shown in Figure 5.2

For the honing-rod knife jitter (x-axis) the p-value (Feedback Type) = 0.07920 $\geq 0.05 = \alpha$. And, the values for p-

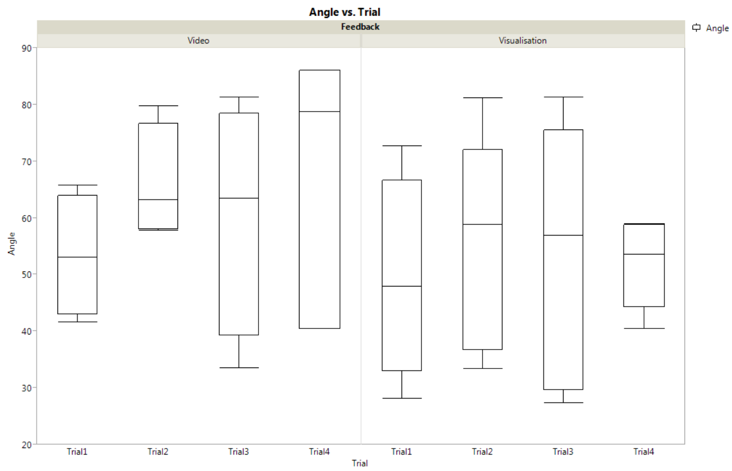


Figure 5.2: Box plot for impact angle from two-way ANOVA results

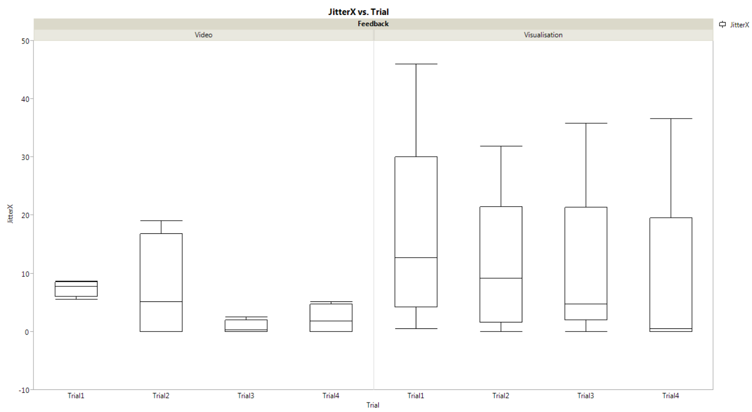


Figure 5.3: Box plot for jitter (x-axis) from two-way ANOVA results

value (Trial) = 0.5517 $\geq$ 0.05 = α, and p-value (interactions) = 0.2710 $\geq$ 0.05 = α. The results are as shown in Figure 5.3

For the honing-rod knife jitter (y-axis) the p-value (Feedback Type) = 0.58215 $\geq$ 0.05 = α. And, the values for p-value (Trial) = 0.37272 $\geq$ 0.05 = α, and p-value (interactions) = 0.4838 $\geq$ 0.05 = α. The results are as shown in Figure 5.4

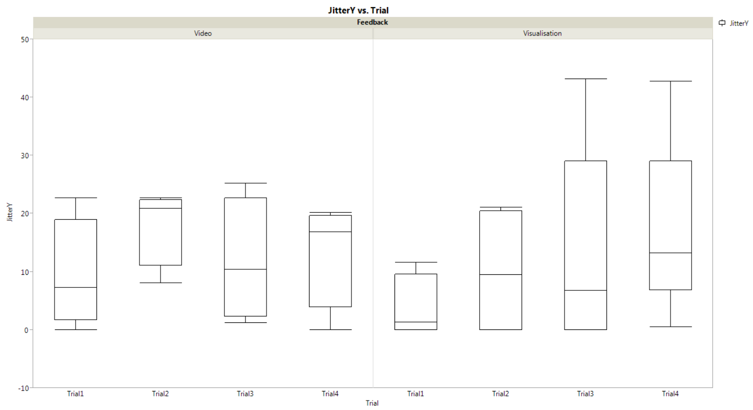


Figure 5.4: Box plot for jitter (y-axis) from two-way ANOVA results

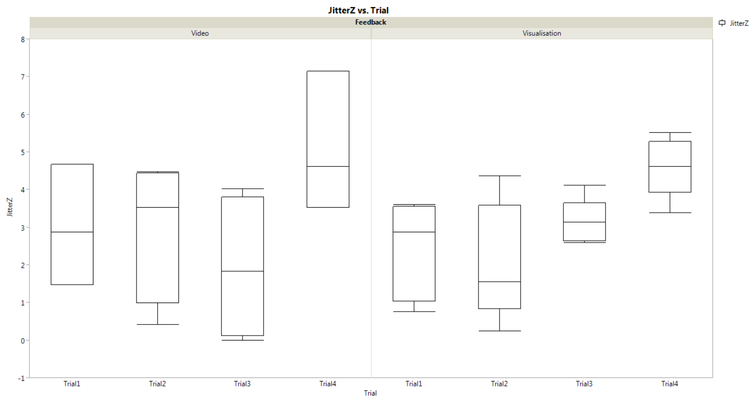


Figure 5.5: Box plot for jitter (z-axis) from two-way ANOVA results

For the honing-rod knife jitter (z-axis) the p-value (Feedback Type) = 0.75605 $\geq$ 0.05 = α. And, the values for p-value (Trial) = 0.00769 $\leq$ 0.05 = α, and p-value (interactions) = 0.0165 $\leq$ 0.05 = α. The results are as shown in Figure 5.5

5.6 Discussion

Using two-way ANOVA both hypothesis are rejected; no significance was found. However, it is important to note

Both hypotheses rejected due to lack of evidence that our results were limited by certain factors.

Change in reference origin might be a limitation

First of which is that we had asked the users to place the honing on a marked box on the table which served as the origin of the Vicon Nexus 3D space. Although, the calibration was unchanged since the collection of the expert's data, there is a possibility that the user's origin point was skewed.

More trials are perhaps required for witnessing any change

Further, four trials may not be sufficient to see improvement in the results. There is need to verify what is the number of trials which is enough to enable all users to learn the skill.

Missing data from users might be a limitation

Also, we had missing data because 2 of the participants recorded only 9 strokes instead of 10. Consequently in our data analysis we had to exclude the information regarding the tenth stroke from the remaining participants.

Possibly more users are needed for the user study

Another possible reason for obtaining unexpected results could be that the number of users was less. While it is a commonly held belief that a minimum of 5 users is sufficient for user testing, the number of users generally depends on the scope of the study.

5.7 Summary

To conclude the user study we must say that the quantitative analysis didn't provide any insights on if or how the independent variables affect the dependent variables. From our analysis we can say that this was due to missing data points or limited number of users or the number of trials could have been too little to show any change or the origin reference point was changed among users.

Users' comments contrary to data analysis results

Nonetheless, the answers of questionnaires answered by the users and the comments received after each study were encouraging and contradictory to the results obtained from quantitative analysis.

It was not easy to judge movements from video

After the first viewing the video feedback the first time, the users reported that they found it difficult to understand how the knife and honing should be held properly because the knife in the video was larger than knife provided during the user study. The visualization feedback on the other hand had no such issues because it was an abstract representation.

The user's also complained that while the video did give an idea of how to correct the mistakes related to angle and jitter, the video didn't tell them anything about their performance other than the fact that they had a mistake. The users were pleased with the way the jitter visualization allowed them to compare their performance relative to the expert's performance.

Video provided static feedback, it didn't allow for reflection

Most of the users understood how to read the visualization feedback after the first trial and reported that they would not want a higher fidelity visualization for the task at hand. The users also expressed their dissatisfaction towards the video feedback saying that after two trials the video didn't provide any additional information and certainly couldn't tell them how the mistake should be corrected.

Video didn't provide any new information after two trials

It is important to note that several users stated that they thought that the abstract visualization would be most helpful when provided in real-time. This contradicts our rationale of *When is feedback delivered?* as explained in 4.2.1 "Rationale". Nevertheless, this is something that we need to test in our future work.

Real-time feedback desired by users

Post the study most of the participants felt that they were quite confident about performing the knife honing task. Moreover, they appeared quite eager to learn more skills with the assistance of visualizations such as those designed by us. The suggestions of skills provided by the participants includes shooting, playing an instrument, sword fighting, flying an airplane and rowing.

Users were confident about performing knife honing

Chapter 6

Summary and future work

This chapter presents a retrospection of what has been done in this thesis. It summarizes the problems addressed in the work and contributions for the field of human computer interaction. After that, an outlook is provided for the next steps in the future.

6.1 Summary and contributions

Summary of the work

Overall, this work is an analysis of suitable performance features for a skill with the objective of designing feedback visualizations which can provide sufficient information for correction of mistakes when learning the skill's movements. From our review of the related work in Chapter 2 "Related work", we found that there was a need to digitize a skill. Thus, this thesis described how a skill's performance measurement criteria may be determined on the basis of discussions with the expert, observation of the expert's performance, and insights from dimension space constructed to assist in making design choices. Furthermore, this thesis presented feedback visualizations designed on the basis of deduced performance measurement criteria and tested these visualizations as compared to videos to understand their effect on user's performance.

Chapter 3 "Taxonomy and Dimension Space" introduced background information about types of skills and described the scope of skills which interested us the most — Fine, closed, internally paced, discrete and individual skills. From motor learning literature, basics about feedback and human movement patterns were presented. Then, the Dimension Space for assisting in design decisions was explained which had six axes — Feedback timing, Feedback information content, Capture perspective, Output capability, User experience variability and Tracked unit. We also constructed Dimension Space plots for few of the studies discussed in related work and gained further understanding of the design choices that have been made in existing research.

Chapter 4 "Performance Measurement Criteria and Visualization" then provided a clear specification of the task to be learned - Knife Honing. With the help of domain expert and available literature, key aspects and performance measures as well as improvement criteria to evaluate a learner's progress were identified. We established that there are two major criteria for evaluating a learner's knife honing skills; first, the angle between the honing rod and knife, and second, the stability of the honing rod. Based on available information and understanding, we also finalized on the appropriate methodology to capture the skill movements using Vicon Nexus motion capture system. Afterwards, using the captured data we determined thresholds for the criteria established to evaluate any learner's performance. Subsequently, with Q-O-C notations, the Dimension Space was analyzed and the abstract feedback visualizations build on the design choices were presented.

Chapter 5 "User study" described the pilot and main user study with the task of knife honing conducted to verify the level of improvement in learner's performance with the designed feedback visualizations. However, the results could not prove the hypotheses. The unexpected results are probably due to missing data and less number of trials. Majority of the users claimed in the post-study interview that after the first two trials the videos didn't provide any extra information to help improve their performance while the visualizations gave them precise information about their movements.

Thus, this thesis has systematically completed the three contributions as listed in Chapter 1 "Introduction". We presented the performance features for the task of knife honing and described a Dimension Space as our first contribution. The methodology followed could be adopted to determine the performance criteria and key indices to evaluate any skill which falls under our selected scope. Besides this we designed and evaluated feedback visualizations which were characterized by the determined evaluation parameters. And because, the user study didn't prove the validity of the designed visualization it leaves a lot of room for future work and improvement.

6.2 Future work

Machine learning could be employed to strengthen the error detection process

Our work falls under the category of systems which deal with enabling acquiring of a task-oriented knowledge. This naturally implies that it interacts with humans and it would be great if they closely parallel human abilities of learning. In other words, it would be great if it was capable of learning, memory and pattern recognition. This would not only allow detection of more performance indicators, but also improve the method in which the mistakes of the learner is judged. This is where machine learning comes into play (Michalski et al. [2013]); to be specific, supervised learning algorithms could be applied to build a system which is capable of extracting a model of movements from the expert and assessing the performance of novice users. The data we collected for the purpose of establishing the threshold values for the performance measurement criteria can be used as the training set for our task of knife honing; the expert's data as the positive samples and the data from the novice users as the negative samples. By applying a strong low-pass filter the repetitions of knife honing can be detected and the extracted features can be used to train a Hidden Markov Model. Hence, in the future we can extend this work to include the machine learning approach and also address the designing of higher fidelity feedback visualizations.

Appendix A

Background Information Questionnaire

This appendix contains the questionnaire used to gather the background information about the user during both the data collection procedure and the final user study to evaluate the error visualization system.

Background Information - Questionnaire

Participant's ID _______

Age _______

Gender _______

Do you have or have you ever had any medical problems with the movement of your hands? If yes, please elaborate.

____
____
____
____

For what purpose do you generally use knives?

____
____

What kind of knives do you use?

Figure A.1: Background Information Questionnaire page 1

How often do you use these knives in a day/week? How many minutes on an average per week?
____
____

Do you have any experience with sharpening knives? If yes, with which tools have you sharpened knives so far?
____
____
____

Figure A.2: Background Information Questionnaire page 2

Appendix B

Data Collection Questionnaire

This appendix contains the questionnaire used to gather information as to the mistakes that the users thought they had made.

Data Collection – Questionnaire

What mistakes do you think you made during

Trial 1?

Trial 2?

Trial 3?

Figure B.1: Data Collection Questionnaire

Appendix C

Stroke Performance Table

This appendix contains the Stroke Performance Table for User 1. The table was constructed in the similar manner for the remaining users. The table was completed by reviewing videos of the participants by the expert and us, to indicate the errors. We also found certain other errors apart from the ones that we were already investigating. The description of these errors is given as follows

- OP1 - Knife movement along the edge is incorrect: User doesn't pull down the knife in an arching motion instead the user either pulls down the knife in a manner that it is almost parallel to the table or in a straight downward manner.
- OP2 - Side is not switched while knife sharpening: User sharpens one side the required number of times in a row rather than switching sides and performing the knife sharpening action alternately on each side.

Since, the occurrence of these errors was limited to only a very small fraction of users, we didn't consider them while designing our visualizations.

Annotator	UserID	Session	Stroke	HasAngle-Problem	HasHoningRodAngle-Problem	HasHoningRod-Stability-Problem	HasRange-Problem	HasOther-Problem	Other-Problem-Details
Urmi	User1	1	1	NO	YES	NO	YES	YES	OP1
Urmi	User1	1	2	NO	NO	NO	YES	YES	OP1
Urmi	User1	1	3	NO	YES	NO	YES	YES	OP1
Urmi	User1	1	4	YES	NO	NO	YES	YES	OP1
Urmi	User1	1	5	NO	NO	NO	YES	YES	OP1
Urmi	User1	1	6	YES	NO	NO	YES	YES	OP1
Urmi	User1	1	7	YES	NO	NO	YES	YES	OP1
Urmi	User1	1	8	YES	NO	NO	YES	YES	OP1
Urmi	User1	1	9	YES	NO	NO	YES	YES	OP1
Urmi	User1	1	10	YES	NO	NO	YES	YES	OP1
Urmi	User1	2	1	YES	NO	NO	YES	YES	OP1
Urmi	User1	2	2	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	3	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	4	YES	NO	NO	YES	YES	OP1
Urmi	User1	2	5	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	6	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	7	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	8	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	9	NO	NO	NO	YES	YES	OP1
Urmi	User1	2	10	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	1	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	2	NO	YES	NO	YES	YES	OP1
Urmi	User1	3	3	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	4	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	5	YES	NO	NO	YES	YES	OP1
Urmi	User1	3	6	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	7	NO	NO	NO	YES	YES	OP1

Figure C.1: Stroke Performance Table for User 1 - Page 1

Annotator	UserID	Session	Stroke	HasAngle-Problem	HasHoningRodAngle-Problem	HasHoningRod-Stability-Problem	HasRange-Problem	HasOther-Problem	Other-Problem-Details
Urmi	User1	3	8	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	9	NO	NO	NO	YES	YES	OP1
Urmi	User1	3	10	NO	NO	NO	YES	YES	OP1
Expert	User1	1	1	YES	YES	YES	YES	YES	OP1
Expert	User1	1	2	YES	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	3	NO	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	4	YES	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	5	YES	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	6	YES	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	7	YES	NO	YES	YES	YES	OP1, OP2
Expert	User1	1	8	YES	YES	YES	YES	YES	OP1, OP2
Expert	User1	1	9	YES	NO	YES	YES	YES	OP1, OP2
Expert	User1	1	10	YES	NO	YES	YES	YES	OP1, OP2
Expert	User1	2	1	YES	NO	YES	NO	YES	OP2
Expert	User1	2	2	NO	YES	NO	NO	YES	OP1, OP2
Expert	User1	2	3	YES	NO	YES	NO	YES	OP2
Expert	User1	2	4	NO	YES	NO	YES	YES	OP2
Expert	User1	2	5	YES	NO	YES	NO	YES	OP2
Expert	User1	2	6	NO	NO	YES	YES	YES	OP1, OP2
Expert	User1	2	7	YES	NO	NO	NO	YES	OP2
Expert	User1	2	8	NO	NO	YES	YES	YES	OP2
Expert	User1	2	9	NO	NO	NO	NO	YES	OP2
Expert	User1	2	10	NO	YES	YES	NO	YES	OP2
Expert	User1	3	1	NO	NO	NO	NO	YES	OP2
Expert	User1	3	2	NO	NO	YES	YES	YES	OP2
Expert	User1	3	3	NO	NO	YES	NO	YES	OP2
Expert	User1	3	4	NO	NO	YES	NO	YES	OP2
Expert	User1	3	5	NO	NO	NO	NO	YES	OP2

Figure C.2: Stroke Performance Table for User 1 - Page 2

Annotator	UserID	Session	Stroke	HasAngle-Problem	HasHoningRodAngle-Problem	HasHoningRod-Stability-Problem	HasRange-Problem	HasOther-Problem	Other-Problem-Details
Expert	User1	3	6	NO	NO	YES	NO	YES	OP2
Expert	User1	3	7	NO	NO	YES	YES	YES	OP2
Expert	User1	3	8	NO	NO	YES	NO	YES	OP2
Expert	User1	3	9	NO	NO	YES	NO	YES	OP2
Expert	User1	3	10	NO	NO	YES	NO	YES	OP2

Figure C.3: Stroke Performance Table for User 1 - Page 3

Appendix D

Error Visualization Trial Review Questionnaire

This appendix contains the questionnaire used to gather information about the understanding of the user related to the feedback provided for the mistakes of knife-honing rod angle and honing rod jitter.

Error Visualization System – Trial Review Questionnaire

After Trial 1

1. Was the first feedback related to knife-honing rod angle able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. Was the second feedback related to honing rod stability able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

After Trial 2

1. Was the first feedback related to knife-honing rod angle able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. Was the second feedback related to honing rod stability able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

After Trial 3

1. Was the first feedback related to knife-honing rod angle able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. Was the second feedback related to honing rod stability able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

After Trial 4

1. Was the first feedback related to knife-honing rod angle able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. Was the second feedback related to honing rod stability able to convey the mistake you made?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Figure D.1: Trial Review Questionnaire

Appendix E

Error Visualization System Post Performance Questionnaire

This appendix contains the questionnaire used to collect information from the user post the knife honing performance related to the user′s confidence.

Error Visualization System – Post Performance Questionnaire

1. Tools required to perform the knife sharpening skill conveyed the movement you needed to perform with your hands?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

2. The information content in the video feedback presented to you was enough to correct your mistakes?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

3. The information content in the abstract visualization presented to you was enough correct your mistakes?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

4. You would prefer higher fidelity visualization as compared to the ones you saw?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

5. Can you imagine learning other skills with a feedback interface such as this?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

6. Do you feel confident about performing the knife sharpening skill after this training session?

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Figure E.1: Post Performance Questionnaire

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