Applied Interdisciplinary Concepts

for Designing Visual Media

Within Interactive Neurorehabilitation Systems

by

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ABSTRACT

As the application of interactive media systems expands to address broader problems in health, education and creative practice, they fall within a higher dimensional space for which it is inherently more complex to design. In response to this need an emerging area of interactive system design, referred to as experiential media systems, applies hybrid knowledge synthesized across multiple disciplines to address challenges relevant to daily experience. Interactive neurorehabilitation (INR) aims to enhance functional movement therapy by integrating detailed motion capture with interactive feedback in a manner that facilitates engagement and sensorimotor learning for those who have suffered neurologic injury. While INR shows great promise to advance the current state of therapies, a cohesive media design methodology for INR is missing due to the present lack of substantial evidence within the field. Using an experiential media based approach to draw knowledge from external disciplines, this dissertation proposes a compositional framework for authoring visual media for INR systems across contexts and applications within upper extremity stroke rehabilitation. The compositional framework is applied across systems for supervised training, unsupervised training, and assisted reflection, which reflect the collective work of the Adaptive Mixed Reality Rehabilitation (AMRR) Team at Arizona State University, of which the author is a member. Formal structures and a methodology for applying them are described in detail for the visual media environments designed by the author. Data collected from studies conducted by the AMRR team to evaluate these systems in both supervised and unsupervised training contexts is also discussed in terms of the extent to which the application of the compositional framework is supported and which aspects require further investigation. The potential broader implications of the proposed compositional framework and methodology are the dissemination of interdisciplinary information to accelerate the informed development of INR applications and to demonstrate the potential benefit of generalizing integrative approaches, merging arts and science based knowledge, for other complex problems related to embodied learning.

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CHAPTER 1

INTRODUCTION

1.1 Context and Intent of this Work

Over the last decade, efforts have increased to expand the applicability of interactive media systems design to address more complex problems related to education, health, community awareness, and creative practice. The growth of emerging areas such as virtual rehabilitation (Cobb, Brooks, Anthony, and Sharkey, 2013) and serious games for education (Michael & Chen, 2005) has been accelerated by a number of factors, including the availability of low cost sensing and computational tools (e.g. OptiTrack, Nintendo Wii, Microsoft Kinect) as well as a growing interest in facilitating multidisciplinary collaboration for expanded research problems (programs such as the National Science Foundation Integrative Graduate Education and Research Traineeship, ASU School of Arts, Media and Engineering, NYU Interactive Telecommunications Program, USC Institute of Creative Technologies, and MIT Media Lab). However, such rapid diversification of interactive media applications has resulted in an emergent field of media design that is not yet well defined, as it has outgrown the limited scope of well-established, disciplinary approaches.

Existing approaches to media design are well established in part because they cover narrow subsets of experience. For example, media designed to provide assistance, such as a traffic light, explicitly communicates information to guide human activity within daily life. On the other hand, the intent of media designed for reflective or contemplative experience, such as the arts, is to promote engagement and provoke a complex cognitive and/or emotional response (Dewey, 1934). Such examples of media design are optimized to be assistive or reflective because they operate within very specific contexts. Though effective in promoting engagement and reflection, the traditional arts not only require a high degree of control of the participant's physical experience (e.g. gallery, theater or performance hall) but their direct application to functional activity in daily life is improbable and highly participant-dependent. While assistive media are ubiquitous and easily applied within daily life, ultimately they serve no additional

function beyond a localized application (e.g. a traffic light is not designed to persist in memory but rather fade into the background of daily function).

Assistive versus reflective media represent opposing sides of a functional continuum of media design, where function in this context describes the designer's intended usage of the media by others. Clear examples of media artifacts (e.g. arts) or media systems (e.g. traffic lights) can be found at the extremes of this function continuum but the middle area is lacking in well defined examples of media-based applications that provide both assistance and facilitate refection. Though the middle of this continuum is sparse in examples, fields like human-computer interaction (Dix, Finlay, Abowd, & Beale, 2003) and interaction design (Cooper, Reimann, & Cronin, 2007) have begun to define several key design dimensions for optimizing ease of use of computing interfaces and designing media ranging from mobile to desktop products that connect multiple aspects of user experience. Interactive systems for education, health or creative practice require media that promote different types of function ranging from assistance to reflection, and furthermore, such systems require consideration of more design dimensions than function alone. While several of these dimensions will be discussed in Chapter 4, Figure 1 displays a simplified two-dimensional space to illustrate where existing examples of media applications fall with respect to the function dimension versus participation. Note that as media applications move away from the extremes (e.g. purely assistive, purely reflective), they fall within a higher dimensional space for which it is inherently more complex to design.

While disciplinary approaches have allowed for in depth investigation and valuable knowledge, the scope of individual disciplinary models is too narrow to cover a large area of the space described in Figure 1. Consider the case of designing an interactive system for stroke rehabilitation. A strictly motor learning perspective might identify a strong overlap between the underlying mechanisms of learning elemental movement patterns in development, and re-learning movement patterns following stroke (Subramanian, Yamanaka, Chilingaryan, and Levin, 2010). A purely game-centered approach to rehabilitation might emphasize the need for highly engaging interaction with media that prioritizes recontextualization of the experience (Suits, 2005)

to remove the person from the feeling of performing rehabilitation exercises. While both of these approaches offer valuable insight to the problem, each lack key aspects of a likely more effective integrative approach: to provide appropriate context aware experiences that incorporate assistive aspects to guide the person toward self-evaluation. This is not to suggest that approaches between different disciplines can simply be merged. Continuing with the previous example, a software developer can structure an interactive program that follows therapy regimens, or a clinician can appropriate off-the-shelf games to achieve interactive systems for rehabilitation. Although both of these approaches may result in systems that satisfy a larger subset of the stroke survivor's rehabilitation experience than in the single discipline approach, they still cover a smaller subset of daily experience than desirable. For example, a fixed game design might sustain a specific exercise within therapy but does not generalize to other tasks.

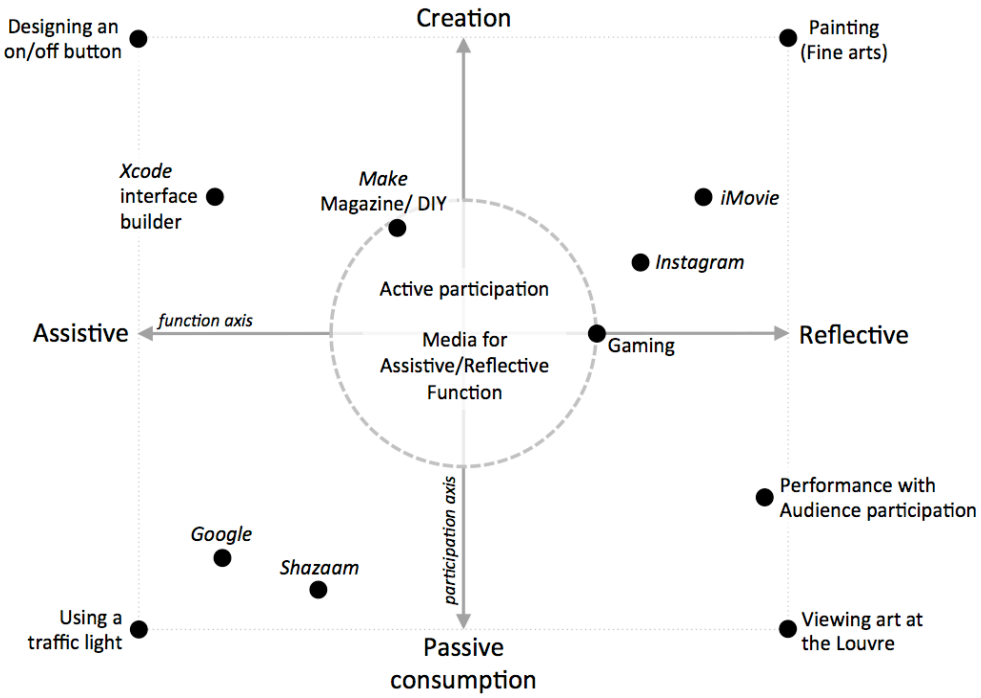


Figure 1. Examples of media plotted in terms of function versus participation. Function and participation are two of many dimensions that influence interactive media design. Media along the function dimension can range from assistive to reflective. Participation in the media's creation can range from sole creator (e.g. painting) to consuming media as a spectator (e.g. viewing a painting in a gallery). Methodologies have been well established for designing media applications placed along the periphery of this space, while the center of this space is more difficult to design for and hence not well defined.

The knowledge from different disciplines required to address the diverse needs of such an expanded experience space must be distilled into high-level interdisciplinary concepts, or common approaches to solving problems that are not discipline specific. For example, to assist in designing systems for interactive stroke rehabilitation, the fields of motor learning and embodied interaction design can each be expanded based on underlying commonalities pertaining to understanding and designing for human experience. Rehabilitation approaches grounded in motor learning can increase the opportunity for functional recovery following stroke (Krakauer, 2006). Embodied interaction attempts to integrate phenomenological approaches to understanding human activity to the design of interactive systems (Dourish, 2004). Although embodied knowledge arises from simple everyday activities, we accomplish activity among a highly complex network of factors and influences generated by the relationship between the user and environment (Dourish, 2004; Krakauer, 2006). This approach necessitates a contextual understanding of activity and experience and parallels the concept of repetitive task training for rehabilitation (Wolf, Blanton, Baer, Breshears, & Butler, 2002) by allowing for the breaking down of daily activity into a series of goal-oriented actions repeated throughout the day in various forms. Furthermore, completion of multiple action goals with different degrees of similarity contributes to the accumulation of embodied knowledge. Both motor learning and embodied interaction therefore stress the importance of knowledge gained through the body's experience by interacting with the world. By drawing this strong parallel, core ideas that underlie seemingly diverse fields and perspectives can be used to more effectively guide the design of systems for interactive stroke rehabilitation.

Such high-level interdisciplinary concepts are also necessary to facilitate communication across members of an interdisciplinary team of system designers trying to reach a common goal. However implementation of a system still requires that each team member be able to interpret and execute domain-specific knowledge. For example, an engineer and a media designer will semantically reduce the high-level concept of feedback differently. Because the engineer's implementation focus lies elsewhere, s/he might simplify the feedback as an output signal that

changes based on the user's input. On the other hand the media designer must have knowledge of how to utilize several formal elements (e.g. color, shape, key) and compositional techniques (i.e. overall structure over space and time) grounded in the visual and sonic arts to design effective feedback for an experience that aggregates to help form the participant's mental model. To realize the system from design to implementation, each member must be able to utilize the necessary component-level knowledge (e.g. compositional and formal skills, mathematical and modeling skills) to execute his/her part.

This emerging area of system design, which requires a hybrid of knowledge synthesized across multiple disciplines to address challenges relevant to daily experience, is referred to as *experiential media systems*. Within this dissertation the focus will be on a subset of the experiential media space: media design for interactive neurorehabilitation (INR), with specific examples of applications designed for upper extremity rehabilitation for stroke. INR utilizes interactive technology to enhance neurorehabilitation therapy, which aims to maximize functional recovery among individuals who have suffered a neurological injury. INR systems link motion-sensing technology with visual and audio feedback to create engaging, interactive experiences that provide detailed information on performance in a manner that facilitates active engagement and sensorimotor learning (Kizony, Katz, & Weiss, 2003; Gaggioli et al., 2004; Sveistrup, 2004; Holden, 2005; Piron et al., 2005; Edmans, Cobb, & Pridmore, 2009; Laver, George, Thomas, Deutsch, & Crotty, 2012; Turolla et al., 2013).

INR is an expanding field with the potential to significantly impact a growing population of adults facing long-term disability ("What is stroke?", 2014). While loss of functionality can be regained through rehabilitation (Page, Gater, & Bach-Y-Rita, 2004) increasing healthcare costs have led to severe reductions in the amount of therapy provided (Anderson, Jamrozik, & Stewart-Wynne, 1994). Furthermore, while it was previously believed that recovery would hit a plateau approximately six months post stroke (Jorgensen, 1995), research has demonstrated that recovery can extend into multiple years following stroke (Whitall, McCombe, Silver, & Macko, 2000; Duff, Chen, & Attygalle, 2010; Lo, Guarino, & Richards, 2010). INR systems can provide

lower-cost alternatives to traditional therapy that encourage active learning and require reduced supervision. Such systems have the potential to be deployed in the home (Cobb et al., 2013) and ultimately increase self-directed participation in daily activity. While the potential for significant impact is clear, large-scale evidence supporting the optimal methodology for INR design is lacking. Harnessing information from other disciplines can help advance the design and dissemination of such systems to accelerate testing and future data-driven approaches to designing highly adaptive and customizable systems that cater to the needs of each individual.

The primary aim of media systems for INR (or other embodied learning contexts) is to facilitate the participant's gradual achievement of a complex learning goal while reducing dependence on augmented (external) feedback. The complex learning goal for INR is independent functional participation in daily life (i.e. activities of daily living or ADLs). Figure 2 shows a simplified visual representation of these factors as axes of the INR problem space, where the learner's use of augmented feedback is described by the vertical axis and the complexity of activity being trained is described by the axis projecting out of the page. The primary sources of augmented feedback are the coach (the physical therapist) and the interactive media systems; while feedback from the coach is initially the most dominant source of feedback applied, over time, the media feedback is used to a greater extent, followed by the ultimate use of learned internal models. While the space shown in Figure 2 represents only two axes of a multidimensional problem space for INR, the breadth of experiences for which system designers much account is fairly large. To sufficiently address such a broad experience space, a network of systems is required, of which each should be optimized for a particular stage of training but also support a cohesive aggregate experience contributing to the participant's internal model. Furthermore, given that participants face different movement challenges and respond to therapy differently, among other factors, the required sequence and amount of time spent within each phase of learning can be different for each participant. Movement in multiple directions between systems should therefore also be supported (e.g. a participant may need to repeat exposure to supervised training with a coach after engaging in unsupervised training).

Composing media for one INR system therefore requires consideration of the *entire* INR continuum to support a cohesive experience that contributes to the participant's learning (formation of internal models) no matter the therapy path taken. As illustrated in the presentation of media applications with respect to function versus participation in Figure 1, the type of media design required for INR does not fit within more traditional approaches to strictly assistive or reflective media, but instead requires design that falls within the middle area. Thus an experiential media approach, which merges hybrid knowledge from multiple disciplines, could potentially inform methods for INR media design. Furthermore to compose for multiple systems in a consistent manner, a methodology based on common interdisciplinary concepts could also help guide media designers to create multiple systems that still contribute to a cohesive experience.

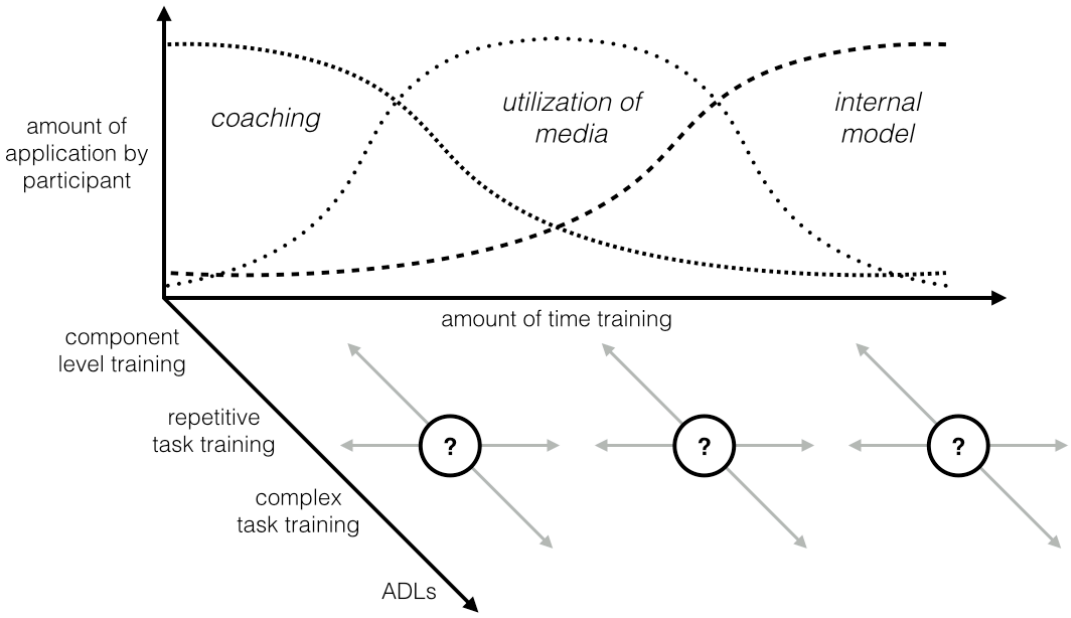


Figure 2. Example of a simplified INR problem space. The vertical axis shows the amount of application of external feedback from either the coach or interactive media system. The axis coming out of the page shows the range of activity trained. The nodes with question marks represent potential states of learning in which a participant might reside; arrows indicate that participants might transition to a state in any possible direction in this space. The goal of experiential media systems for INR designed for this space is to gradually reduce the participant's use of external sources of feedback as they develop internal models. At the same time, the participant should be advancing towards increase participation in activities of daily living.

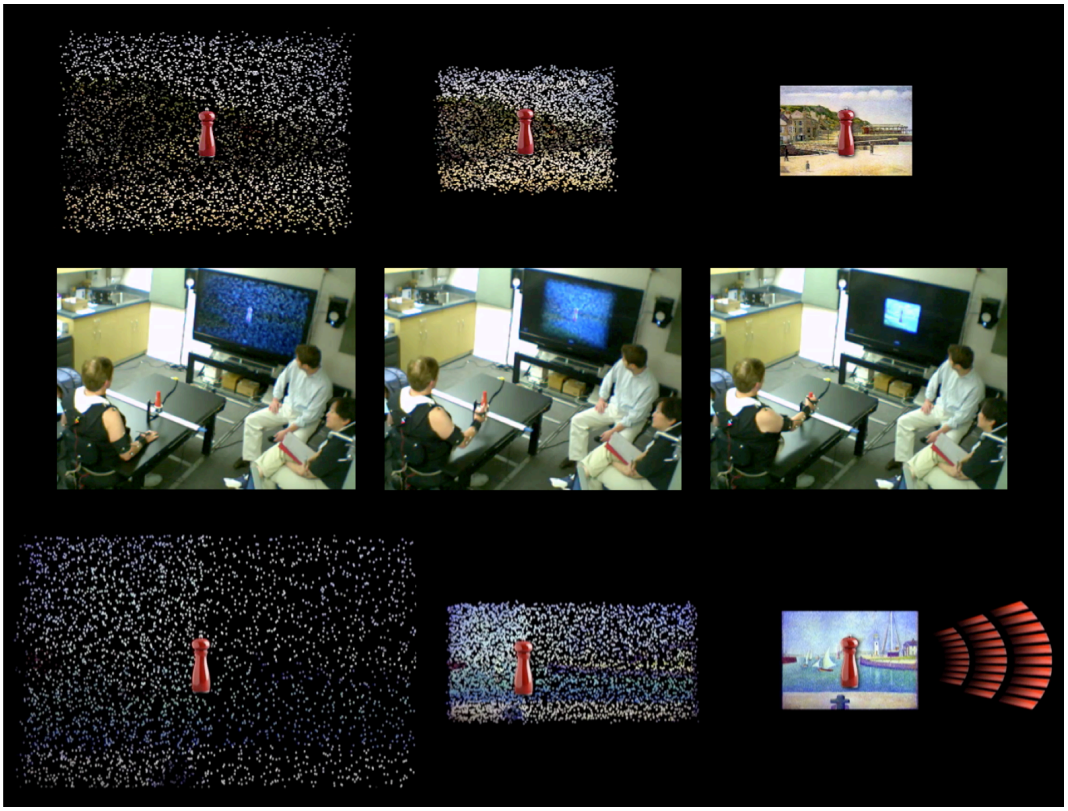
The primary contributions of this dissertation are (1) to help establish interdisciplinary concepts for designing visual media for INR by harnessing evidence and well-established practice from motor learning and rehabilitation, interactive learning, media arts, and interactive computing, and then (2) use these concepts, with arts knowledge, to develop a media compositional framework for a network of INR systems for stroke, with examples to illustrate the framework's application. Based on the author's background in the visual arts, a focus on composing visual media is explored.

While the interdisciplinary concepts and compositional framework provided in this dissertation, as a collection, are specifically applied to INR and stroke rehabilitation, such an approach may also assist the development of media for other interactive learning contexts. INR presents a diverse sampling of challenges including a user base of various levels of ability and activity training that ranges in terms of type, supervision level, location, and timescale. Such features cut across several dimensions of experiential media design and can inform approaches for connecting distributed experiences for general learning, behavior modification and/or awareness, creative practice, among other areas. Designing for distributed mediated experience has become increasingly relevant in mainstream personal technologies as designers aim to facilitate continuous, cohesive experiences across an ecosystem of personal computing and wearable devices (Ashton, 2009; "IOS8 Continuity", 2014).

1.2 Overview of the Author's Contribution within the AMRR team

The clinical Adaptive Mixed Reality Rehabilitation (AMRR) System was designed by the AMRR team at ASU to establish proof of principle that real-time interactive feedback can effectively communicate multiple aspects of reaching performance to stroke survivors within a therapist-assisted training environment. The author's minor contribution to this system was a visual summary of the participant's trajectory error displayed following the AMRR system's real-time feedback to enhance the participant's offline reflection on his reach performance. The team successfully tested the AMRR system and audiovisual feedback environment in a comparative

study to traditional therapy (Duff et al., 2013), results of which are summarized in Chapter 3. Figure 3 shows the real-time visual feedback designed by team member Loren Olson while Figure 3c shows an example of the trajectory error summary following.



(a) (b) (c)

Figure 3. Visual feedback environment for the AMRR system. The forward movement of the participant's hand pushes the particles back to reassemble the image, as shown in panels (a-c). The particle coalescence on the top row reflects an efficient reach without spatial error, while the particle coalescence on the bottom row reflects inefficient reaching performance with deviation to the right. The image stretches with the magnitude and in the direction of error. Error is then summarized with red discrete error bars, as shown in panel (c).

The author was also responsible for co-developing within a small team of students a system for unsupervised training, referred to as the home-based Adaptive Mixed Reality Rehabilitation (HAMRR) system, which trains a range of simple to complex tasks without continuous supervision by the therapist. Specifically the author designed and implemented a multi-level visual environment that provides feedback on various aspects of the stroke survivor's reaching performance. The environment, of which examples are shown in Figure 4, responds to

multiple aspects of the participant's movement performance across various types of training tasks, structures of activity, and training sensitivities. The visual environment also uses various feedback design strategies to communicate movement performance, ranging from direct performance display to abstract inference of a narrative, to help facilitate self-evaluation over long timescales of training. Multiple contexts of training are connected using an overarching distributed narrative (content is semantically coherent across activity, space and time) to connect physical action to several levels of visual summary, as well as gradually facilitate the participant's self evaluation.

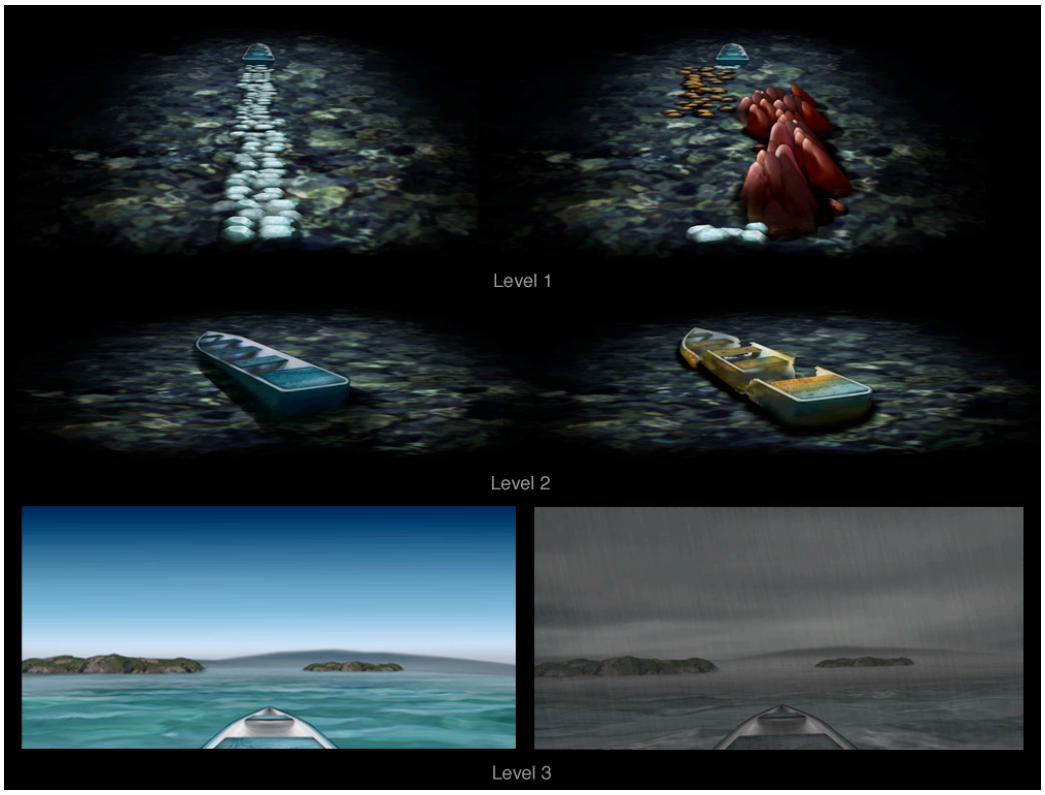


Figure 4. Three-leveled visual feedback environment for the HAMRR system. Visual feedback is provided on three different levels of activity. The left column depicts examples of efficient movement while the right depicts examples of inefficient movement. Level 1 provides real time color-based feedback on magnitude of trajectory error (not shown), followed by an on-screen summary of a rock path illustrating the magnitude and direction of error. Level 2 feedback is provided following a set of reaches; a straight boat is used as a visual metaphor for efficient movement while various broken boats indicate different types of inefficient movement. Level 3 feedback, presented after a complex reaching task, provides an audiovisual narrative summary based on task completion and quality of movement performance.

The feasibility of the HAMRR system was evaluated within a semi-supervised environment in the clinic. Two system units were deployed in a multi-site study at the Rehabilitation Institute of Chicago (RIC) and the Center for Rehabilitation Medicine at Emory University. The author led the experimental setup for the Emory University site, of which responsibilities included system installation, training the physical therapists, collaborating with Emory personnel to develop study protocols, administering training for three stroke survivors while at Emory, and providing remote assistance for the training of two additional stroke survivors administered by Emory physical therapists. Study execution, data collection, and analysis were the result of collaboration with Michael Baran, the other student co-lead of this project who was responsible for the RIC site.

In conjunction with this study, the author developed an iPad application for the therapists to better assess the participant's experience while using the HAMRR system. The application allows for the therapist to administer a custom interactive questionnaire; capture video of the patient performing standardized tasks; as well as edit, annotate and compose sequences of video for the patient to see his progress over longer timescales than were offered by the system. These tools also asked the therapists to rate and annotate additional videos of participants performing the standardized tasks using a custom rating scale developed in collaboration with Emory personnel, to further the team's understanding of the relationship between kinematic evaluation and therapist assessment.

The final contribution is formalizing the theoretical bases of past and current approaches used by the team to design the AMRR system for supervised training within a pair of companion publications (Lehrer, Attygalle, Wolf, & Rikakis, 2011; Lehrer, Chen, Duff, Wolf, Rikakis, 2011). These publications reference principles in motor learning, interactive computing and the arts to produce guidelines for designing interactive media for stroke rehabilitation for common movement challenges faced by stroke survivors. Based on these publications, the author's design and development work, as well as the collective system development by the MRR lab, key

interdisciplinary concepts and a compositional framework have been synthesized for designing experiential visual media for INR.

1.3 Summary of Dissertation

Chapter 2, section 1 discusses prior work related to designing visual media for INR. A survey of recent INR systems using interactive visual media environments is first presented. Types of environments reviewed include first person point of view representations, game-based scenarios, simple non-representational scenes, and self-directed exploratory environments. Understanding these current approaches to visual environments for INR provides valuable insight into the advantages and limitations of different types of media environments used. However, because large-scale data is lacking, no conclusions can be drawn from the present body of evidence on what aspects of training are most effective and which type of media design should be used for a given application or context. Although currently evidence within INR alone is inadequate to determine the optimal methodology for media design, several of the problems requiring investigation within INR have been addressed in more narrow contexts within other fields of study. Chapter 2, section 2 discusses relevant prior work in motor learning, interactive learning, media arts, and interactive computing interfaces, which have collected more substantial evidence to support principles (or well-established guidelines) for best practices within their respective fields.

An experiential design methodology suggests that several of these principles overlap or share commonalities across disciplines, despite the fact that each discipline focuses on a particular subset of daily experience. Thus extracting high-level interdisciplinary concepts from these principles can support understanding of a broader experience space. Collective evidence supporting these principles across various fields of study suggests that their application will be effective in emerging fields such as INR, and can be used to bolster informed design for INR while more substantial evidence within the field is being collected. The INR systems for supervised and self-directed training created by the AMRR team have utilized such a mixed

discipline approach. Chapter 3 provides a summary of both systems and the results from corresponding studies evaluating each system conducted by the AMRR team. Greater detail is provided for the study evaluating the use of unsupervised AMRR given the author's contribution. As did other prior work, these systems have strongly informed the development of the interdisciplinary concepts discussed in the following chapter.

Chapter 4 presents the key interdisciplinary concepts for designing experiential visual media for INR synthesized from prior work. Each concept provides direction as to how a media design feature should be handled with respect to important considerations for movement rehabilitation, and then provides examples using one or more of the AMRR systems. Concepts discussed include how to design the media's function, what representations are appropriate to use based on specific use cases, the extent to which participation should be facilitated, as well as how multiple aspects of performance should be divided across various streams of information, media modalities, and time delivery structures. Then the organized application of these features is discussed in terms of achieving an overall coherent experience over time, activity and space. Finally the importance of coaching and facilitating a network of experiences with various media environments is described.

Chapter 5 presents the compositional framework for authoring visual media for INR systems across contexts and applications, with a focus on upper extremity stroke rehabilitation. The compositional framework demonstrates how interdisciplinary concepts, combined with arts-based knowledge, are used for feedback environments across systems for supervised training, unsupervised training, and assisted reflection. For both the clinical and home-based training systems, the full audiovisual feedback environment is summarized to describe how each feedback component addresses a key movement challenge faced by stroke survivors and adheres to the interdisciplinary concepts described in Chapter 4. In Chapter 6, key aspects of the implementation process are described for the visual media environments designed by the author: a visual summary of movement error in the clinical AMRR training system; a three-leveled

graphics environment used in the home-based AMRR training system, and the iPad application for assisted reflection.

Chapter 7 then revisits the evidence presented in Chapter 3 in order to draw some conclusions on the extent to which evidence collected from the clinical and home-based AMRR studies supports the application of the compositional framework for INR media design. Conclusions are organized in terms of confidence level, in which evidence supported by both studies is presented first, followed by more nuanced exploration into potential ways to evaluate the feedback's effect on movement quality. Chapter 7 closes with more qualitative observations from the clinic and unanswered questions to be considered in future re-design of the visual media. Finally Chapter 8 discusses broader future directions and considerations for INR and beyond. The need for therapy customization and sustaining long-term compliance are discussed as well the opportunity for mobile applications to provide an entry point for merging creative applications with behavioral awareness and preventative health care.

CHAPTER 2

PRIOR WORK IN INR AND EXTERNAL DISCIPLINES

Two areas of prior work relevant to designing visual media for interactive neurorehabilitation (INR) are presented: (1) current and past INR systems utilizing visual media external to the AMRR group at ASU and (2) established methodologies and evidence relevant to INR media design from motor learning, interactive learning, media arts, and interactive computing.

2.1 Prior Work in Visual Media for INR

INR systems that utilize motor learning principles can provide augmented feedback on movement performance for sensorimotor rehabilitation (Kizony et al., 2003; Gaggioli et al., 2004; Sveistrup, 2004; Holden, 2005; Piron et al., 2005; Jung, Yeh, & Stewart, 2006; Edmans et al., 2009; Laver et al., 2012; Turolla et al., 2013). The application of interactive systems to stroke rehabilitation can lead to practice-dependent improvement in motor function of the affected arm (Saposnik & Levin, 2011) and have led to greater improvements in limb function in comparison to conventional therapy (Laver et al., 2005). However, the extent to which such training is more effective than traditional therapy techniques is still under investigation. Due to the diversity of INR systems being investigated, no conclusions can been drawn on which aspects of training are most effective and what type of media design should be used. While an established methodology for designing media for INR systems is lacking, current approaches to INR media design provide valuable insight into the advantages and limitations of different types of media environments utilized.

INR systems can provide digital media-based (audio or visual) or force-based feedback on movement performance to facilitate the patient's self-assessment. While some groups (Adamovich, Fluetb, Tunikb, & Meriansb, 2009; Brochard, Robertson, Medee, & Remy-Neris 2010; Saposnik & Levin, 2011) characterize *virtual reality* systems as any INR system that utilizes digital feedback at various levels of immersion (e.g. ranging from a head-mounted display to a

video game on an LCD screen), the term should be reserved to describe only fully immersive, simulated environments in which no aspect of the participant's physical environment is visible and/or tangible (Garb, 1987) as exemplified in this fully immersive INR system (Perez-Marcos et al., 2012). *Mixed* (or sometimes referred to as *augmented*) *realities* describe environments that use any combination of digital feedback components amidst a visible and tangible physical environment (Milgram & Kishino, 1994). Because mixed realities provide interactive experiences that are situated in physical reality, such environments can embed learners in realistic contexts and therefore potentially provide mediated training that facilitates generalization and transference of knowledge from therapy to activities beyond rehabilitation (Wilson, 1996; Pridmore, Green, Hilton, Eastgate, & Cobb, 2004; Mousavi Hondori, Khademi, Dodakian, Cramer, & Lopes, 2013). Both virtual and mixed reality INR systems may or may not include robotic interfaces that offer physical assistance or simulate haptic feedback (Adamovich et al., 2009). Only systems that use interactive visual media to communicate movement performance of a task will be considered as relevant prior work in this dissertation. Four prevalent categories of INR systems using interactive visual feedback environments are discussed in terms of design motivation, potential benefits and limitations.

2.1.1 First person point of view (some with representation of the end effector). Some INR environments couple movement of the patient's end effector to a digital representation (e.g. the patient's hand controls the movement of a hand viewed from a first person point of view). The digital hand can be superimposed onto a background that is representative of the patient's actual physical environment (e.g. reaching across a table top in a clinic or home) or other contexts (e.g. catching a ball that is pitched across a field (Eng et al., 2007)). Several groups are motivated to use imagery that is easily relatable to the patient's action space based on the action observation hypothesis, that observed actions associated with self-generated or intended actions engage cortical motor observation, planning and execution areas (Buccino, 2001). Some approaches also digitally represent both the affected and less affected extremities despite training uni-manual tasks, based on findings that activation in damaged parts of the motor cortex may be enhanced

by viewing mirrored movements of non-paretic limbs (Ramachandran & Hirstein W, 1998). Proof of concept for action observation has been demonstrated for stroke using fMRI (Garrison, Aziz-Zadeh, Wong, Liew, & Winstein, 2013) and f-NIRS (Holper et al., 2013). The stroke patients who interacted with the catching game described in (Eng et al., 2007) demonstrated improved performance within some clinical measures. A similar concept was applied for the lower extremity after incomplete spinal chord injury by depicting digitally rendered feet in front of various game scenarios, in which flexion/extension by the patient was coupled to different kicking game activities (Villiger, 2013). Patients reported reduced pain and demonstrated increased motor function, though no comparison was made to a control. A potential limitation of these environments is that such representations are not truly matched to what the person experiences in physical reality in terms of detail and point of view. Focus on controlling a mismatched human representation could result in distracting artifacts undesirable for training, based on prior work demonstrating differences in activation among observers who watched a digital representation of an end effector versus a person performing the task in real life (Perani, 2001). Simulated first person point of view scenarios without any representation of the limbs have also been applied to gait training (Fung & Perez, 2011) and upper extremity rehabilitation for stroke (Subramanian, Lourenço, Chilingaryan, Sveistrup, & Levin, 2013). The latter (Subramanian et al. 2013) evaluated the effect of augmented feedback on reaching performance to objects depicted on a screen versus reaching to objects in a physical environment. The mixed environment, which provided a success cue for task completion and overall score, led to greater changes in motor recovery patterns. While evidence exists that utilizing visual media relevant to the task can be beneficial, additional research is needed to evaluate if these highly specific scenarios can generalize to other related tasks and/or sustain patient engagement over long-term training.

2.1.2 Game-based scenarios. Several INR systems such as those described in (Laver et al., 2012) couple the patient's activity to interactions with a game. Such systems can provide external motivation to complete training by coupling activity to a goal and reward system embedded within the gameplay (Koster, 2005). The availability of off-the-shelf game consoles

providing low-cost sensing technology paired with rich feedback environments, such as the Nintendo Wii or the Microsoft Kinect, make these systems attractive to use directly within or appropriate for therapy. The Wii has been accepted by stroke survivors who engaged in Wii sports-based therapy, such as boxing, bowling, tennis, golf and baseball (Yong et al., 2010), and in a separate study, patients who used the Wii demonstrated greater improvement in time performance of various functional tasks in comparison to recreational therapy (Saposnik, 2010) such as playing cards, bingo and other games. While convenient to use in therapy, off the shelf games can result in a weak connection between movement and feedback because many such games were designed for non impaired audiences and contexts that are not appropriate for the task being trained (Deutsch et al., 2011). Also because some games are not contextually relevant to activities of daily life, gains made through gameplay may not transfer outside of the specific context of playing the game. Finally such games can potentially lack an intrinsic reward value for more mature audiences, and as a result may reduce patience compliance over time. On the other hand, custom-designed games for rehabilitation can connect the direction and extent of the participant's movement to visuals on the screen. A custom designed game for targeted reaching movements (Burke et al., 2009) directs the patient to hit various target objects by superimposing their own representation into the game scenario to easily relate feedback given on performance to the task being performed. Another example of a custom game environment (Bermúdez & Cameirã, 2012) maps movement of the right and left arms to directly steer a parasailing character. The custom game design also structures multiple levels of gameplay that connect to a narrative and change based on level of training. While both of these games are customized for training, they allow the patient to visually monitor his entire movement by showing a representation of the person on the screen and rely on the game to consistently drive the action as opposed to having the participant practice tasks with gradually reduced feedback over time or game level.

2.1.3 Simple non-representational environments. In contrast to more detailed game environments, simple non-representational environments typically represent one or very few

movement parameters to avoid providing potentially extraneous, overwhelming or confusing information. For example one INR system (Abdollahi et al., 2013) maps the patient's hand movement to a cursor and directed the patient to follow another cursor controlled by a therapist. Error augmentation was used for both force and visual feedback (distance from the therapist's cursor was accentuated) to draw the participant's attention to the two-dimensional position of his hand. Use of this system in a blinded randomized crossover study demonstrated significant improvement for those who received error augmentation practice as opposed to standard care though gains did not affect functional ability as much as isolated motor ability. Another simple abstract environment (Godfrey, Schabowsky, Holley, & Lum 2010), paired with a robot for hand exercise following stroke, uses two circles to represent the location of the finger and thumb in one scenario and/or respective applied forces in another scenario. Training using this representation, in which the goal was to pass the circles through holes or bypass an oncoming rectangle before the circles are intercepted, led to increased digit ROM with some but less consistent improvements in clinical measures. Another example (Mousavi Hondori et al., 2013) of a system for hand training following stroke, provides simple abstract shapes and sounds based on grasp aperture and task completion respectively; which non-impaired participants were able to utilize to complete tasks without the assistance of a robotic interface. While these environments can improve motor ability with respect to individual types of isolated movements, many are lacking in their potential to affect functional ability. Because functional tasks require knowledge and coordination of several parameters by the mover, an excessive reduction in complexity of action-related information that is often used in simple abstract environments may impede functional rehabilitation (Wulf & Shea, 2002; Huang et al., 2005). Thus augmented feedback for rehabilitation can best leverage motor learning principles if it allows the participant to focus on individual aspects of movement in the context of other key aspects of the trained movement.

2.1.4 Self-directed exploratory. Self-directed exploratory environments focus on using visually rich and engaging media to incentivize experimentation of movement. The patient is encouraged to discover how to interact with the system, rather than being provided directions.

One exploratory system designed for future application in INR allowed users to explore a physical painting with accompanied sonified and tactile enhancements (Le et al., 2013), which engaged non-impaired users during pilot testing and received favorable feedback from participants on the experience. Another exploratory system mapped free-form movements performed by patients with traumatic brain injury to paint-like paths on the screen. The aesthetics of the painted path could be modified depending on preference, and also individual marks could be mirrored to create more complex aesthetic forms that were visually pleasing in symmetry. Resultant paintings were used as summaries to discuss smoothness of movement by the participating therapists (Worthen-Chaudhari, 2013). These environments place the patient in a lower-risk, creative context that promotes autonomous decision-making by the patient (Worthen-Chaudhari, 2013) to promote engagement and empowerment, which can be beneficial to patients (Rizzo, Schultheis, Kerns, & Mateer, 2004) in rehabilitation applications. While such systems are well accepted by patients and demonstrate great potential for therapeutic applications, they have not yet demonstrated the potential to yield significant functional improvements. A potential limitation of such a free-form approach is that unbounded exploration does not translate into gains in function without some constraints such as coupling feedback to goal-directed activity. Furthermore the amount of time required to yield such gains may lead to potential frustrations associated with not seeing results. An environment that pairs goal-oriented training with exploratory training (Mumford et al., 2012) for patients with traumatic brain injury utilized a table-top interface in which patterns and sounds were generated from manipulations of physical objects on the table. Goal-oriented training involved hitting targets with the physical object amidst distractor shapes, while the exploratory training (used at the end of each session) provided an array of objects that the user could hit in any sequence desired to compose visuals and sound. Patients who used the system (for one month amidst continued use of usual care therapy) improved a variety of measures including speed and accuracy of tasks used in the system, but saw mixed results in some standardized clinical measures. While it is unclear what specific contribution exploratory versus goal-directed modes provided, the system designers contend that the added exploratory phase

complements goal-oriented training by placing a greater demand on the volition of the participant without external prompting, which could enhance different aspects of motor control.

2.1.5 Summary of conclusions. Prior work in visual environments for INR support that visual media relevant to task-oriented training can activate areas involved in motor planning and execution of the task and also result in improved performance by patients who have suffered neurological injury. The high specificity of visual representations used however raises questions on if these environments would generalize to other tasks and would maintain engagement over long periods of time. External motivation can incentivize training but still needs to be contextually relevant to functional activity. While feedback should target specific aspects of movement trained, feedback should not over simplify the movement to the extent that it cannot promote understanding of the relationships among multiple movement components. While engaging exploratory feedback can stimulate different types of problem solving that are potentially important to motor learning, such environments requires some constraint so that practice is both efficient and contributes to an overall training goal. Custom-designed media can help tailor feedback to the needs of the participant and the task being trained, but there is currently not a set of comprehensive guidelines for designing media for INR or how to achieve optimal adaptation per person/context. Some of the many unanswered problems faced by system designers for INR are addressed in part within external fields, such as interactive learning and creative practice. The following section reviews methods from other disciplines to help address some of these challenges.

2.2 Evidence from Other Disciplines

Relevant prior work in motor learning and rehabilitation, interactive learning, media arts theory, and interactive computing are presented.

2.2.1 Motor learning and rehabilitation. Approaches to rehabilitation training grounded in motor learning can increase the opportunity for restitution of function following stroke (Krakauer, 2006). Principles in motor learning should therefore inform the design of rehabilitation therapies

by not only establishing guidelines for practice but also types of feedback to use. Feedback should be conducive to both specificity and repetition of exercise within unassisted, goal-directed practice (O'Dell, Lin, & Harrison 2009) by providing both magnitude of error and direction for improvement with respect to the task being trained.

The motor control system relies on structural, generalizable learning for skill acquisition (Mussa-Ivaldi, 1999; Braun, Aertsen, Wolpert, & Mehring, 2009). For example, some kinematic features are invariant across different types of multi-joint movement (Morasso, 1981; Abend, Bizzi, & Morasso, 1981) and should be focused upon within training, as they are the most easily generalizable across different types of tasks (Krakauer, 2006). Because learning occurs within highly individualized contexts (e.g. each individual constructs his own knowledge from first person experience), the path to achieving knowledge can be non-linear and vary across learners. Research in motor learning and other statistical learning processes such as language acquisition (Saffron, 2003) suggest that internal models are formed based on a collection of perceived rules (statistical regularities) and associations (transitional probabilities) that are distilled from a variety of experiences physically engaging with an environment (Saffron, 2003). The formation of generalizable models is supported by distributed practice with variability, which leads to better retention of skilled actions (Schmidt, 1991; Richards & Pohl, 1999; Krakauer, Mazzoni, Ghazizadeh, Ravindran, & Shadmehr, 2006). Studies have demonstrated that when subjects are exposed to varying tasks of similar structure, motor control processes can extract the shared structure of the task (Braun, Aertsen, Wolpert, & Mehring, 2009), suggesting that the human motor control system relies on modular, generalizable learning for skill acquisition. Thus feedback for INR should support the understanding of modular aspects of movement in a variety of training contexts.

Active engagement, challenge, and independent discovery can facilitate neuroplasticity (Kleim & Jones, 2008). Specifically for stroke, problem solving is critical to enhance motor learning (Bach-y-Rita, 2001; Bach-y-Rita et al., 2002; McEwen, Huijbregts, Ryan, & Polatajko, 2009). Feedback that is prescriptive in nature, or directly instructs how to solve a problem, should

only be used in very limited contexts in order to maximize self-assessment and encourage the development of independent movement strategies (Subramanian et al., 2007; Boyd & Winstein, 2006). Though some forms of prescriptive feedback have been identified as effective for novice learners (Timmermans, Seelen, Willmann, & Kingma, 2009), if consistently applied this approach may create dependencies on the feedback (Kizony, Katz, & Weiss, 2003) and therefore is less likely to promote active, independent learning (Boyd & Winstein, 2006; Boyd, Quaney, Pohl, & Winstein, 2007). Feedback therefore should facilitate active engagement to support parallel cognitive and motor learning by the stroke survivor (Cirstea & Levin, 2007) and encourage problem-solving problem solving during therapy (Kleim & Jones, 2008; Schaechter, 2004).

Multimodal integration refers to how the nervous system integrates information from multiple senses in order to effectively interact with our environment in a meaningful way (Spence & Squire, 2003). Sensory modality appropriateness (Welch & Warren, 1980) refers to the extent to which a specific sensory modality provides the most accurate or appropriate sensory information (Spence & Squire, 2003). Visual feedback is best suited for communicating spatial information, such as providing guidance for correcting trajectory errors in goal-directed arm movement (Sarlegna & Sainburg, 2009). Audio feedback is best suited for communicating temporal knowledge (Yantis, 2000). For example, movement patterns requiring complex timing or synchronization can be trained effectively through musical rhythm (Thaut, 2007; Chen, Penhune, Zatorre, 2008; Trehub & Hannon, 2008) and has been applied to effectively entrain motor patterns in stroke rehabilitation (Thaut, 2007). Tactile feedback is utilized by the haptic system to confirm target acquisition (Zahariev & MacKenzie, 2007) and modulate grip force for stable grasping (Johansson & Westling, 1984). Tactile feedback is also used to detect when contact is made or broken with surfaces in the environment, which can be applied for anticipatory control based on memory from previous interactions (Johansson & Westling, 1984) and can provide guidance during a supported (target located on a table) reaching task. Feedback therefore should support multimodal integration by utilizing the most appropriate modalities to communicate different aspects of movement performance.

Understanding the balance between restitution of body functions and compensatory behavior, amidst completion of an action goal, is crucial for designing therapies that are well suited for the patient at his or her particular stage of recovery (Levin, Kleim, Wolf, 2009). Rehabilitation therapies should not seek to achieve full restitution, irrespective of patient capability (Levin, Kleim, Wolf, 2009; Kwakkel, 2009). Rather rehabilitation therapies must be adjustable and adaptable to fit the patient's prognosis for recovery and progress during therapy without increasing patient frustration. Feedback should therefore not only provide information with respect to accomplishing a task goal, but also help the patient distinguish between different types of movement and their contribution to achieving the functional goal. More complex aspects of movement performance, their integration and relationship to function cannot necessarily be explicitly communicated effectively, as these can involve implicit processes within the mover (Wulf & Prinz, 2001). Thus different types of feedback are necessary to most effectively communicate different movement components, such as continuous monitoring of the endpoint versus intermittent monitoring of trunk compensation.

2.2.2 Interactive learning (Constructivist theory and studio arts practice). Constructivist/constructionist learning theory suggests that some exploratory activities (e.g. playing with Legos) can provide rich learning experiences that enhance problem solving (Pappert & Harel, 1991). However to promote active learning, interactive environments must continuously balance challenge and appropriate cognitive load based on the learning goal (Wilson, 1996). Both explicit and implicit learning are often present in most learning scenarios with varying amounts of contribution from each (Slusarz & Sun, 2001), where explicit learning is faster and more easily achieved and implicit learning requires extended practice to yield understanding. Variation in the degree of problem solving required by different types of feedback that facilitate both explicit and implicit learning can therefore provide an experience that is balanced between encouragement and self-discovery to optimize learning (Schmidt, 1991; Slusarz & Sun, 2001). In a similar manner to motor learning, constructivist learning also suggests that feedback should promote various degrees of problem solving to maximize self-discovery but minimize frustration.

Constructivist/constructionist learning theory also emphasizes embedding learners in realistic contexts (Wilson, 1996). Learning scenarios should not be oversimplified but should incorporate multivariate information to support effective decision-making, as is often necessary in real-world circumstances (Davis & Sumara, 2006). Mixed realities, which combine digital information with physical components, can provide interactive experiences situated in physical reality that facilitate transference of knowledge from learning scenarios to outside contexts (Pridmore et al., 2004).

Constructivist/constructionist learning theories also support that knowledge is organized into emergent structures (Pappert & Harel, 1991) that contribute to a complex internal model, which continuously evolves (Davis & Sumara, 2006) as more experience is collected. While several aspects of learning are non-linear and complex, through self-driven experience the learner can begin to acquire knowledge seemingly spontaneously (Pappert & Harel, 1991; Davis & Sumara, 2006). Rich environments fostering collaboration with others to share perspectives are a critical aspect of constructivist learning to gain new perspectives on a problem (Rushton, Brainerd, & Pressley, 1983) and achieve a well-formed model (Davis & Sumara, 2006). Feedback should promote learning of knowledge structures underlying phenomena, and do in a manner that aggregates, or accumulates to inform an overarching knowledge goal.

Studio arts practice can provide models for structuring experiential learning by breaking down training into elemental and composite exercises (Richter, Obrist, & Britt, 1995). What makes studio arts training complex and necessitates an experiential approach is that students cannot be explicitly directed on how to develop many of the skills that are critical to advancing. Students must internalize and learn to generalize both technical and conceptual proficiencies. But most importantly, personal work must emerge from individual experiences in the world, self-discovery and previous, more basic stages of learning (Moon, 2013). Foundational elemental exercises include the study of color and value (Arnheim, 1974) (e.g. receiving explicit guidance on how to produce color wheels or value sensitivity scales). Early on simple composite training is introduced to promote connections between elements in relevant contexts (e.g. value is most

critical to rendering two-dimensional representations of form; every color has an associated value (Arnheim, 1974)). Training builds in complexity in a hierarchical fashion, where aspects of training have different levels of abstraction (“Studio Arts, Newcomb Art Department”, 2014). Gradually, value can be used as a tool for more abstract concepts like composition and mood (e.g. the mood of a dark, low value range scene versus a high contrast one). The deconstruction process (how the learner determines the manner in which low-level components contribute to high-level goals of painting) is hidden and highly individualized depending upon the learner, but each learner should be exposed to various levels of abstraction in order to facilitate connections. Similar techniques have been applied to understanding the shape and structure of tonal music by considering music to be a composite of multiple layered structures in Schenkerian analysis (Forte & Gilbert, 1982) and reducing musical structures into the most basic elemental units (Westergaard, 1976) to understand compositional design. Structured learning in the arts, similar to approaches in constructionist learning, draws a strong parallel to the idea of modular learning in motor learning and training of motor elements in the context of overall tasks.

2.2.3 Media arts theory and design. When providing media-based feedback on performance of a task, selection of the appropriate media content can be extremely influential on how the task is perceived and performed by the participant. Presenting a virtual scene that depicts an arm grasping a cup, for example, may evoke memories of past failed attempts and consequences (Sanchez-Vives & Slater, 2005) that can negatively affect performance. Furthermore, virtual environments that attempt to realistically depict human forms may introduce undesirable artifacts that distract the viewer such as the uncanny valley phenomenon, which refers to a negative emotional response to human likenesses that are close to human but not exact (Vinayagamoorthy et al., 2004; Mangan, 2007). Visual content used in feedback should change based on the degree of dissociation desired. Providing a visual representation that is abstract or does not directly reflect the participant and the activity can promote recontextualization, which facilitates a new perspective or understanding towards a learning scenario by changing the context of an existing challenge (White, 1998). Recontextualization has

a diverse history of application within the arts (Bashkoff, Klein, & Turrell, 2001; Gude, 2004) to reinvent visual forms in order to promote new understanding of a subject matter.

Similar to modality appropriateness, the arts use affordances of specific media to communicate different types of content. The use of visual perspective is an intuitive communicator of spatial depth (Knill, 2007; Saxena & Chung, 2008) and visual point of view (Arnheim, 1974), which can easily be acquired by the viewer (e.g. viewing an intimate portrait head on versus a distant landscape from overhead). Visual content can also be effective for summarizing information (Xu, Chen, Sundaram, & Rikakis, 2006) because its static nature allows for extended review and reflection. Music and the sonic arts through the application of chord sequences and melodic contour (change in pitch over time) can impart a sense of forward movement (Siegmeister, 1965; Ratner, 1966; Piston, 1978; Cohen, 2010) and can be used to encourage, monitor, and time a progression towards the completion of the action goal (Schmuckler, 1989). Because perception of audio is statistical and is retained, it can handle multiple feedback streams and extract relationships among them. The communication of complex audiovisual narratives through film often utilize the visual medium for the explicit narrative while music can be used to communicate more implicit aspects such as mood, change in time, and the pacing (Chion, Gorbman, & Murch, 1994).

As previously discussed, efforts to understand the underlying mechanisms of recovery following stroke suggest that active engagement, challenge, and independent discovery are critical for effective therapy (Saffron, 2003; McEwen, Huijbregts, Ryan, & Polatajko, 2009). The arts provide an exemplary medium for implicitly shaping the individual's experience without explicit instruction (Dewey, 1934) so that the individual can independently draw conclusions about his experience. For example, the painting tradition capitalizes on our inherent perceptual sensitivities to patterns of value and color to achieve an intuitive and meaningful visual experience (Arnheim, 1974). To accomplish such distillation of experience through art, the arts must draw from our physical experiences in the world (e.g. the observer of a painting intuitively senses warmth through color, or movement from loose brushstrokes, by relating to internalized

past experiences in the world). While encounters with art can tend towards aesthetic experiences shared by multiple participants, the individual can also still arrive at unique associations resulting from personal experience, which lends the use of artistic compositions as an adaptive medium per person, per context. The arts can also provide guidance on achieving long-term engagement, a key consideration for designing media for INR, by connecting individual experiences to an overarching whole: consider how each chapter in a novel leads to anticipation of culmination (Wong & Pugh, 2001).

Interactive arts installations such as (Snibbe, 2014; Utterback, 2014) allow for the spectator to become part creator by affecting the art piece through his own input, a process referred to as active participation. Tools for media authoring and sharing such as *iMovie* and *Flickr* as well as DIY culture and *Maker* fairs have also been considered agents of participatory culture by empowering the any individual to follow creative pursuits using enabling tools. Interactive art installations are sometimes referred to as generative (Pearson, 2011) because an external data source is generating its final output, as opposed to fixed form media, such as a painting or pre-composed musical piece, which is unaffected by the spectator. While generative feedback can lead to exploration and experimentation to discover one's individual effect on the system, some types of fixed-form media can have a prescriptive effect: for example, a prominent, regular rhythmic pattern may encourage someone to attempt to move in the rhythm of the music rather than a different timing pattern (Thaut, 2007; Repp & Penel, 2004). Familiar musical songs have one fixed ideal form, the form with which the user is familiar (Levitin, 2006).

Arts compositional form refers to the key components of a structural unit (e.g., key elements within a literary, artistic or musical composition) and the meaning that arises from the interrelationships among these components. Form integration and coherence refer to the use of media composition principles to integrate individual feedback streams into one meaningful and contextually relevant (coherent) form, thus decreasing the amount of cognitive effort required for understanding the multimodal interaction. When designing complex mediated experiences, form integration is facilitated by the appropriate feature selection for constructing individual feedback

components (e.g. modality selection) and use of appropriate compositional strategies for merging individual feedback components into a unified context. For example the use of lighting in painting can unify smaller components into larger sections that guide the eye through a visual hierarchy, where large blocks of value (e.g. dark regions versus light regions) are perceived first followed by smaller components of a painting. Another example that draws from well-established compositional techniques of film theory and practice (Chion, Gorbman, & Murch, 1994) is using the visual modality to communicate the explicit aspects of the narrative and the audio modality to provides more implicit information, such as underlying affect, encouragement and timed progression. Thus arts composition techniques can provide a potential means for unifying complex multimodal information (previously discussed in the context of sensorimotor learning) in a manner that is intuitively understood.

2.2.4 Interfaces for interactive computing.

While interactive media can augment our interaction with the physical world in a meaningful way (e.g. providing a success sound when a task is complete), complete immersion within a digital space (e.g. head mounted display that simulates the task) in some cases can lead to disconnected observation and control as opposed to promoting our natural way of learning and understanding environments through our physical bodies (Dourish, 2004). Designing for embodied interaction, in which embodiment refers to possessing and acting through a physical manifestation with the world, can promote active exploration (Dourish, 2004; Rogers & Price, 2004) by the learner. In addition to using visual media that is non fully immersive, the amount of detail and location of the visual media's presentation cannot distract the participant from the knowledge goal (e.g. a misplaced LCD screen can cause interference). Mixed reality environments can promote embodied interaction by offering various levels of digital immersion and locations for displaying visual content.

Although embodied knowledge arises from simple everyday activities, the process of obtaining embodied knowledge is not a simple phenomenon. Interactive learning is managed by the continuous process of coupling, separation, and re-engagement among the body, an external

tool, and an action (Dourish, 2004). Focus on completing the action goal (such as browsing a webpage for specific content) allows for coupling the tool (a computer mouse) and the action (moving the mouse while searching the webpage). Coupling means that the activity is being undertaken without conscious awareness of how the body is using the tool to accomplish the action goal. Failure to achieve the action goal causes decoupling (browsing the webpage and using the mouse become separate components), which allows for exploration of performance components towards achieving the action goal (contemplation of how to better orient the mouse so that it functions properly again). Finally, re-engagement is the re-coupling of tool and action that allows for renewed focus on achieving the action goal (Dourish, 2004). Tool/action coupling is also mirrored in the theory of embodied cognition (Varela, Thompson, & Rosch, 1992), as interaction with the environment through one's body is in fact how one perceives the environment. In this case, the body is the tool that is accomplishing the action. Such phenomenology-based approaches to understanding embodied knowledge through coupling among action, body, and tool are highly relevant to systems focusing on functional recovery. During rehabilitation, the action goal, activity, and body function need to be considered together and separately under different circumstances. When using a separate interface (like a Wii remote) connected to non-tightly coupled visual feedback (as in the Wii tennis game application, in which arm movement in the game environment is not mapped to full arm movement of the user), an error in the feedback will first result in a decoupling of technology and body so the user can improve his learning and management of the technology and its artifacts (Dourish, 2004). This intervening process impedes accurate contemplation of the relationships between physical action, tool and body, even for non-impaired users, and significantly increases the learning challenges faced by impaired users.

When considering the phenomenology of mediated experiences, the system designer cannot transmit an experience to the user (Davis, 2003). Experiential media design does not necessitate (nor would benefit from) a complete simulation of daily life, but rather should be designed as an integrative component within the participant's experience space. An experience is

created by the designer's composition of a data representation (e.g. using the affordances of a medium and the selection of formal structures applied) and the participant's "constructive reception" of the media (Davis, 2003). Thus the participant develops a unique internal model of the media being experienced through his interaction with a system. As previously discussed in motor learning and the media arts, designing media that is modular and is organized within an overall structure (composition) can facilitate this representation by highlighting key aspects of the experience and their relationships.

Finally, interactive computing systems stress that systems should adjust based on usage context. The aim of context-aware computing is to design systems that sense more information about the user's activity, location, identity, and time of interaction (Dey & Abowd, 2000). Context aware systems account for the user's goals amidst the presence of constraints, such as internal and environmental factors, relevant to the user's experience (Baldauf, Dustdar, & Rosenberg, 2007). Such concerns are especially relevant to stroke rehabilitation, where the context of disability varies across stroke survivors. The World Health Organization (WHO) defines disability as experiencing physical impairments, activity limitation in executing a task or action, and/or restricted participation in involvement within life situations ("WHO", 2014). Similar to the definition provided by WHO, and in line with the aims of context aware computing, recent qualitative studies (Sumathipala, Radcliffe, Sadler, Wolfe, & McKevitt, 2012) reiterate that disability is dependent upon the stroke survivor, who may feel restricted in only a subset of these factors while others feel they are exacerbated (e.g. resulting from the presence or absence of family members providing support). Thus context awareness reiterates the need for media that is dynamic along multiple dimensions of the user's experience to address these various needs.

2.2.5 Summary of conclusions. Motor learning suggests that feedback should communicate the magnitude of error and direction for improvement with respect to the task being trained. Understanding of modular aspects of movement training in a variety of context should aggregate towards a common knowledge goal. Problem solving should be facilitated to encourage active learning. Multimodal integration should be supported by utilizing the appropriate

modalities to communicate aspects of movement performance. Finally feedback should be catered to the types of movement performance being communicated.

Interactive learning also suggests that feedback should vary the degree of problem solving to promote self-discovery but reduce frustration. Complex, multivariate information as in the real world should be communicated. Experiences should support the emergence of knowledge structures learning that aggregate and structured learning as in studio arts practice.

Media arts and theory suggests that content should change based on the degree of dissociation desired. Affordances of specific media should be used to communicate different types of content. Arts based principles can be used to shape experience intuitively and sustain engagement, while a coherent compositional form can hold the experience together through form integration. Generative feedback can allow for exploration while fixed-form feedback can instruct.

Interfaces for interactive computing discuss the benefits of promotes embodied interaction. Well-designed interfaces can supports coupling, separation, and re-engagement among the body, an external tool, and an action as discussed by Dourish (2004). Designers should make an experience that supports construction of a representation of key aspects of the experience and their relationships. Changes to the experience should be based on context of the user and external factors.

CHAPTER 3

PRIOR WORK IN INR SYSTEMS THAT USE A MIXED DISCIPLINE APPROACH

This chapter presents an overview of the INR systems developed by the Adaptive Mixed Reality Rehabilitation (AMRR) group at Arizona State University using a mixed discipline (experiential media system) approach. The clinical AMRR system was developed for supervised detailed training of simple repetitive tasks in the clinic, while the home-based AMRR system was developed for training of more complex, multiphase tasks with little to no supervision in the home. Complementary assessment tools were also developed to facilitate reflection for unsupervised training. Together, these systems are applied to facilitate a complementary network of experiences for stroke rehabilitation, as shown in Figure 5, to address the span of the INR problem space. Both the clinical and home-based systems have been evaluated with stroke survivors in two different studies by the AMRR team. An overview of systems and results are presented here to support the validity of a mixed discipline approach, as it forms the basis of later chapters' discussion and application of interdisciplinary concepts.

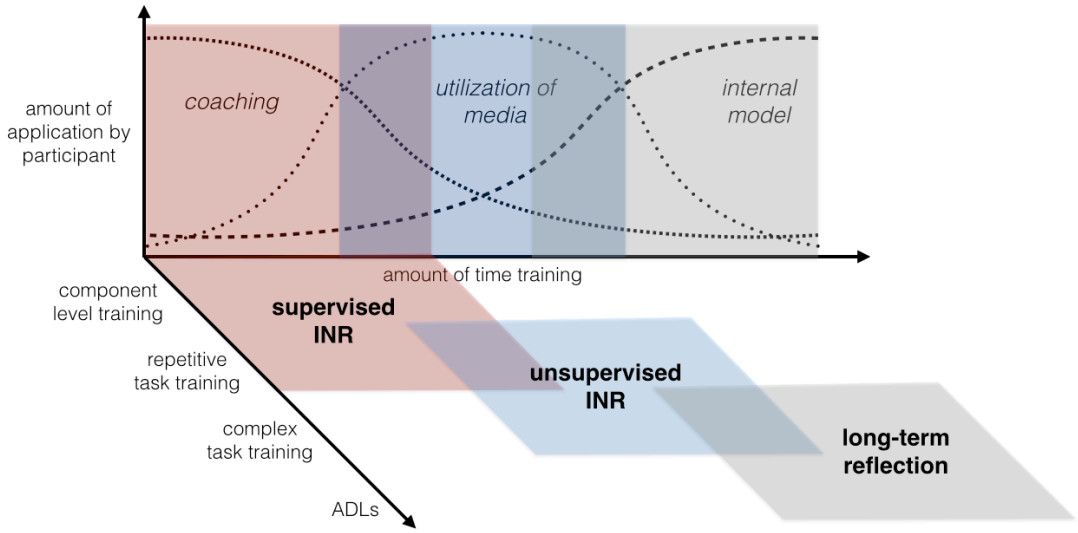


Figure 5. Network of AMRR systems to address the span of the INR problem space. From left to right: Red pertains to clinical AMRR training, blue pertains to home-based AMRR training, and systems optimized for the grey space have not yet been designed. (However tools for assisted reflection used in conjunction to unsupervised INR begin to address issues related to long-term reflection.) Each system addresses a progressively more complex activity training space (shown as the red, blue and grey square projections on the bottom of the space) while gradually reducing the participant's reliance on coaching and utilization of the media to internal models (shown as the red, blue and grey projections on the top of the space).

While more detailed results of the clinical AMRR study are provided elsewhere (Duff et al., 2013), the AMRR system and study provide an important foundation for later work in unsupervised training and are summarized below. The author's minor contributions to the AMRR system and study include the design of the trajectory summary feedback component and a rotation serving as supervising media expert (responsible for working with the therapist to decide on protocol implementation during therapy) for three participants. The treatment and outcomes from the study evaluating the home-based AMRR system are presented in more detail given the author's contribution outlined above.

3.1. Clinical AMRR System Overview and Study

The Clinical Adaptive Mixed Reality Rehabilitation (AMRR) system provides detailed evaluation information and interactive audiovisual feedback on the performance of a reach and grasp task for training supervised by a physical therapist. The system tracks the participant's movement using 14 reflective markers worn by the participant on his back, arm, and hand. Interaction with target objects on the table is tracked by sensors embedded within the targets, and the extent of support provided for the participant's torso and back is monitored by force sensing resistors embedded within the chair. Key kinematic features are extracted and used for computational evaluation of the participant's performance, which generate the interactive feedback experienced by the participant and can also be used to assist a clinician's assessment. Each mediated reach begins with a digital image appearing on the screen, which breaks apart into several minute segments of the image, referred to as particles. As the participant moves his hand towards a target location, the hand's forward movement pushes the particles back to reassemble the image and simultaneously generates a musical phrase. The abstract feedback used within the AMRR system does not directly represent the reaching task or explicitly specify how to perform the reaching movement (e.g., the feedback does not provide a visual depiction of a trajectory to follow). Instead, movement errors cause perturbations within the interactive media

that emphasize the magnitude and direction of the error (e.g., an excessively curved trajectory to the right stretches the right side of a digital image). The abstract feedback also re-contextualizes the reaching task into performance of the interactive narrative (image completion and music generation), temporarily shifts focus away from exclusively physical action (and consequences of impaired movement) and can direct the participant's attention to a manageable number of specific aspects of his performance (e.g. by increasing sensitivity of feedback mapped to trajectory error) while deemphasizing others (e.g. by turning off feedback for excessive torso compensation). Refer to Video 1 to see a demonstration of the clinical AMRR system in use. The system is highly adaptive in that the therapist can adjust components (e.g. feedback or physical components of the system) in real time to accommodate the participant throughout training. The clinician may also use physical or verbal cues to provide coaching as necessary to facilitate the overall experience. A demonstration of the clinical AMRR system in use is provided in Video 1, listed in Appendix E. More detail on the interactive feedback is provided in Chapter 5.

The AMRR system was compared to dosage-matched traditional upper extremity therapy based on changes in validated clinical assessments and kinematic performance of trained and semi-trained tasks that were measured before and after therapy was completed. Results from the study comparing supervised AMRR therapy to traditional therapy have been described in (Duff et al., 2013). In summary both AMRR and traditional therapy groups demonstrated significant improvement in the WMFT and motor section of the FMA. However only members of the AMRR group significantly improved their overall performance of kinematic parameters evaluated in both the trained and untrained tasks, with relatively low variance among improvements, while the traditional therapy group did not show significant improvement in either. The two distributions of percentage change for overall kinematic performance for the trained task were found to be statistically different between the AMRR group and the control group. Even though each participant in the AMRR group received individualized training catered to his/her needs, AMRR therapy induced highly consistent improvement in movement quality with low variance, suggesting that feedback stylized movement across participants. These findings demonstrate the

potential of mixed reality INR to support directed improvements in movement quality (stylization) and functionality in an integrative manner. Finally neither group had significant increased in the Motor Activity Log scores, which measures the participant's self-reporting of amount and quality of use of the affected arm in activities of daily living. These results suggest more effort should be made to improve the connection between training in the clinic and increased participation in daily life at home.

3.2 Home-based AMRR System Overview and Study

3.2.1 System overview.

The Home-based Adaptive Mixed Reality Rehabilitation (HAMRR) system is designed for long-term use in the home. A participant trains with a range of simple to more complex tasks without supervision, except for a once per week visit by the physical therapist to discuss progress and/or address any problems faced with the week's training. The system tracks a reduced number of movement features, primarily from a single reflective marker worn on the participant's wrist and a set of 4 markers worn on the torso, complemented by pressure sensors embedded within the chair to monitor torso movement and sensors embedded within the target objects to monitor manipulation. Abstract feedback is provided at three different levels of activity. The first level provides real time and summary visual feedback per reach, related to trajectory error and task completion and/or audio feedback related to reaching speed. The second level of feedback is given following a set of reaches and consists of composite audio and visual metaphors that describe the overall movement quality of the group of reaches. The third level of feedback, presented after a complex reaching task, provides an audiovisual narrative summary based on task completion and quality of movement performance. Each of these levels contributes to an overarching story structure (illustrated in Figure 3) in which increasing task challenge leads to richer audiovisual feedback summaries. The three tiers of feedback and training structure are organized into a reductive hierarchy, and the overall sequence of exposure to each tier can be non-linear (e.g. the participant jumps across levels in both directions) to facilitate connections of low-level movement components with high-level

movement quality. Whereas the clinical system emphasized detailed real time assistance by the media amidst a therapist who could also offer summary evaluations, the aggregate experience of the home system is designed to facilitate self-evaluation over multiple scales of activity and time. As such the majority of component-level media design shifts from highly detailed concurrent feedback to predominantly reflective feedback summaries. Refer to Videos 2 through 5 listed in Appendix E to see a demonstration of the home-based AMRR system in use. Video 2 provides an example of instruction provided before Level 1 interaction, while Videos 3, 4, and 5 show training sets for the three interaction levels. More detail on the interactive feedback is provided in Chapter 5.

The Training Monitoring iPad application was designed for use by the therapist during the weekly visits for unsupervised training, and can be used to administer and video-record multiple standardized tasks that are partially or semi-trained by the unsupervised system. Once the video is taken the therapist can use the Training Monitoring application to review these videos, segment them into individual reaches, and tag the reaches with an overall quality label and detailed comments. The tagged videos are stored in a bank the therapist uses for composing a video story on the participant's progress and areas for improvement. The summarized video story provided each week by the therapist allows the participant to begin comparing the strategies he has been independently developing with the therapist's assessment. Each week the therapist can select from any of the past videos that were tagged to arrange them into an updated video story. As the stories change, the participant can gain insight into how his progression is shaping over timescales that are broader than those covered in the system training. The Training Monitoring app also provides a template for administering a questionnaire about the stroke survivor's experience with the system, such as ease of use, overall mood following system use, and self-perception of progress during training.

3.2.2 Study evaluating unsupervised training in the clinic. A multi-site pilot study was conducted to evaluate the usability of the therapy and feedback protocols of the HAMRR system during one week of therapist-assisted training sessions, followed by four weeks of patient-led

(unsupervised) sessions. The study was administered in the clinic to evaluate feasibility and observe all participant interactions. The following sections provide an overview of procedures.

Screening and Evaluation. Each participant was screened to verify eligibility to participate, using the following tests: the *Montreal Cognitive Assessment* to evaluate cognitive impairment in areas such as short-term memory, language and attention; the *Geriatric Depression Scale* to screen for depression in an elderly population; *Range of Motion assessments* to assess range of motion in the right arm and hand; a custom *Sensory Perception Test* to verify aspects of sight and hearing such as color blindness, visual field, reading, and pitch discrimination; and the sitting portion of the *Upper Extremity Fugl Meyer Assessment (UEFM)* to assess reflexes, sensation, pain and motor function of the affected upper extremity. Resulting participant demographics of those enrolled are listed in Table 1.

Table 1

Subject demographics for the home-based AMRR study

ID	Age	Sex	Race	Months post-stroke*	Lesion Location*	Impairment
1	63	M	Black	14	L posterior frontal ischemic	Mild
2	69	M	Indian	44	L ICH (fronto-parietal)	Mild
3	65	M	Black	31	L pontine infarct	Mild
4	47	M	Black	26	AVM rupture	Mild
5	56	M	Black	28	L Internal Capsule	Mild
6	49	M	Black	18	L MCA (Middle cerebral artery)	Mild/Mod
7	50	M	Black	15	L basal ganglia hemorrhage	Moderate
8	44	F	Black	13	Ischemic left pons	Moderate

*All subjects are right side affected and have had only 1 stroke.

Eligible participants then completed evaluation measures to provide baseline values of both clinical assessments and kinematic performance of tasks before beginning treatment. An evaluating clinician performed the following validated clinical measures during the pre-training, post-training and one month follow-up evaluation visits: the *Wolf Motor Function Test (WMFT)* assesses performance of the affected upper extremity during 15 timed tasks and 2 strength tasks; the sitting portion of the *Upper Extremity Fugl Meyer Assessment (UEFM)* (if not already measured during a same-day screening); and the *Motor Activity Log (MAL) Quality of Movement*

(QOM) questionnaire that captures how well the participant is using the affected upper extremity during activities of daily living.

After baseline clinical measures were recorded, the following tasks were also performed by the participant while movement was captured by the HAMRR system's optical tracking system: *Trained Movement Task* of reaching to grasp a stable 5" tall cone placed at the participant's midline, repeated 10 times; *Semi-trained Movement Task* of reaching, grasping, transporting a portable cone or cylinder object over a 5" diameter, 8" inch long paper towel roll lying on its side, repeated 10 times; *Untrained Movement Task* of reaching to turn a key set with a box fitted with a lock (following specifications of the WMFT), repeated 3 times. Table 2 lists the kinematic features that were analyzed per task assessed on evaluation days.

Treatment. Within a week of the screening/evaluation visit, the participant began treatment. The treatment consisted of 15 visits over the course of 5 weeks. The first three training visits were performed under the direction of the treating therapist, while the remaining 12 were designed to be participant-directed. A task object could be placed at one of the following locations: the participant's midline, ipsilateral, or far ipsilateral. Repetitive training tasks consisted of reaching to touch a flat object, reaching to touch a button, and reaching to grasp a cone. More complex repetitive training tasks included reaching against gravity to grasp an elevated object or reaching to grasp a portable object (cone or cylinder) located on the table and lifting the object to a height threshold. Finally the most complex tasks trained were sequences of tasks: reaching to manipulate one object (e.g. touch a button) then directly reaching to manipulate another (e.g. grasp a cone) before returning to rest; and transport tasks: reaching to grasp a portable object and lifting it against gravity to another elevated target location, then returning the object to its original location (or vice versa in order).

For the first three one-hour training sessions (completed within one week), the therapist guided the participant through exploring the different types of tasks and feedback. During this time, the participant became familiar with how to set up and use the mixed reality system, and also performed reaching movements while hearing and seeing different types of feedback related

to performance. Following observation of the participant during these first three training sessions, the therapist chose one of two predetermined training paths for the participant to follow over the course of the remaining 12 participant-directed sessions. (The therapist had one opportunity to change this decision after the first week of self-directed training was complete given the two paths are identical until the 7th session.)

The training scenarios vary the feedback and tasks used during the 4 weeks of participant-directed therapy and were designed to accommodate different levels of impairment. *Path A (Transport dominant option)* was used for participants who have a wide enough grasp aperture for a cylinder object (with dimensions and weight similar to a filled soda can) and are able to transport the object, with the potential to progressively engage and complete transportation with repetition. *Path B (Transport light option)* was used for participants who have a reduced aperture and may fatigue easily or express discomfort while performing a transport task with the cylinder object. Path B still requires the participant to perform transport-based tasks but at a reduced exposure in comparison to Path A. Finally, *Path C (Transport light option for more extreme reduced grasp aperture)* was used for relatively more impaired (moderate) participants with such reduced finger dexterity and grasp aperture that a cylinder was not a viable option. These participants used a portable cone shaped object with reduced diameter and weight. For these more impaired participants, the therapist was also available during the time of training sessions in case assistance was needed, and at a minimum was also was present for every third training sessions to supervise therapy. Path C participants therefore had at least 4 less sessions that were unsupervised compared to those who engaged in Path A or B. Table 3 lists the training paths selected for each participant.

Unsupervised training sessions at the study sites were provided with oversight for safety purposes. When the participant arrived for the participant-directed training sessions, s/he was instructed to independently follow the instructions on the screen for arranging the therapy objects in the space necessary for a session (example provided in Video 6, Appendix E). The participant was also required to put on a wristband with a passive motion capture marker attached. The

overseer then placed a badge with 4 markers attached to the left side of the participant's chest. Once the table was correctly arranged and sensors worn correctly, the participant began the therapy session. Each session consisted of about 100 reaches over the duration of approximately one hour. The overseer did not offer additional instructions or provide standard assistance in the setup or use of the system, nor was any assistance offered about the content or context of the feedback or the participant's movement performance during these sessions. However, assistance was provided in case of critical technical issues that arose during normal use. "Training monitoring" (TM) meetings, were held before every third participant-directed training session to provide an opportunity for the therapist to assess the participant's experience and answer any questions s/he might have from the previous sessions of training. During TM meetings, the therapist recorded videos of the participant performing tasks without feedback and administered a system experience questionnaire using a custom iPad application. The TM iPad application also provided an interface to edit, annotate and organize videos as a means to provide feedback to the participant the following week. At the conclusion of training, these edited videos were randomized and presented to the therapist (without annotations or labels) in a different iPad application, which asked therapists to rate movement performance for each reaching trial. These ratings were collected for the purposes of comparing the therapist's assessments with kinematics measured by the system for different training tasks. Rating criteria are attached in Appendix A.

Once the 15 treatment sessions were completed, the participant was asked to return within a week of the last therapy session to complete a post-treatment evaluation, and again within 30 days of the post-treatment evaluation to complete a follow-up evaluation. The evaluations performed pre-treatment, post-treatment and at follow-up were identical. Table 4 provides an overview of the evaluation and treatment schedule. Due to the nature of scheduling and the timeline of the R24-funded study at Emory, the evaluating therapist was present for some training sessions to replace the treatment therapist who could not be present. This was kept to a minimum as much as possible and was approximately less than 18 sessions across the 5 Emory participants.

Table 2

Kinematic features analyzed per evaluation task in the HAMRR system

ID	*Task*	*Day Sampled*
A	Key Turn	Pre, Post, Follow-up
B	Transport Over Barrier left to right	Pre, Post, Follow-up
C	Transport Over Barrier right to left	Pre, Post, Follow-up
D	Transport Down	TM 1, TM2, TM3, TM4,
E	Transport Up	TM 1, TM2, TM3, TM4,
F	Cone Grasp	Pre, TM 1, TM2, TM3, TM4, Post, Follow-up

Movement features		*Definition*	*Related Tasks*
f2	Time Until Grasp (sec)	Time between movement start and grasp of key (before turn)	A
f3	Time Until Release (sec)	Time between movement start and initiation of key release	A
f10	Total Time Until Completion	Time between movement start and completion of successful placement of transport object in second position	B C D E
f4	Time Until 5% Max Speed (sec)	Time between movement start and 5% of the maximum speed on deceleration	A F
f6	Extra Speed Phases Until 5% Max Speed	The first phase is identified as the initial prominent acceleration and deceleration by the hand, and an additional phase is defined as a local minimum in the velocity profile beyond the initial phase 5% of the maximum speed on deceleration	A F
f7	Extra Phases until Key Grasp	Number additional phases (see above) until key grasp	A
f5	Path Ratio	Ratio between the length of the reaching path and the length of the straight line between the hand's starting point, the first target location, and second target location (if applicable)	A B C D E
f13 f14	Max Horizontal Error Max Vertical Error	Maximum horizontal/vertical deviations from a reference trajectory. For example, maximum allowable error before feedback was given is 25 mm and 45 mm respectively.	F
f15	Peak Speed (m/s)	The maximum speed of the end-point (within a reach) while moving towards the target from the starting position.	F
f16	Bellness Normalized Area	Compares the shape of the decelerating portion of the velocity profile to a Gaussian curve by measuring the total amount of area difference between the two curves. The reference threshold is 0.25.	F
f17	Jerkiness	Measure of the velocity profile's smoothness, computed as the integral of the squared third derivative of the hand position.	F
f8	Torso Movement Sum	Summation of the torso plate's movement summed in all three directions beyond the allowable threshold determined from calibration.	A B C D E F

Table 3
Training paths assigned for the home-based AMRR study

ID	Impairment	Training path	Training site
1	Mild	A	Emory
2	Mild	A	Emory
3	Mild	A	Emory
4	Mild	A	RIC
5	Mild	A	RIC
6	Mild/Mod	A	RIC
7	Moderate	C	Emory
8	Moderate	C	Emory

Table 4
Evaluation and treatment schedule for the home-based AMRR study

evaluation	*within 7 days before day 1*	Pre-test		
treatment	*supervised week 1*	day 1	day 2	day 3
	unsupervised week 2	day 4	day 5	TM meeting 1 day 6
	unsupervised week 3	day 7	day 8	TM meeting 2 day 9
	unsupervised week 4	day 10	day 11	TM meeting 3 day 12
	unsupervised week 5	day 13	day 14	TM meeting 4 day 15
evaluation	*within 7 days after day 15*	Post-test		
evaluation	*at least 30 days after post-test*	Follow-up test		

Methods for outcomes analysis. Group-level changes among clinical evaluations and kinematic features measured on the post-test and one-month follow-up were each compared to scores measured on the pre-test using a t-test for two dependent means, with a two-tailed hypothesis at $p < 0.05$.

Participant-level kinematic changes were assessed *within* participants by calculating, for each feature, the percentage change in mean between pre and post-tests. Due to low sample size measured within individual participants, no statistical analysis was applied. Alternatively, favorable or unfavorable percentage changes were characterized based on (1) post-test means that did not overlap with one standard deviation of the pre-test mean versus (2) cases in which post-test means do overlap within one standard deviation of the pre-test mean. The latter case may be less conclusive in terms of representing true change, and thus were limited to changes only greater than 5%, but may indicate the direction that a feature may be heading. Last (3) favorable percentage changes that also decrease in standard deviation between the pre and post-tests are also noted. The key task was ultimately excluded from further analysis because over 60% of the data collected was lost due to noisy methods for capturing the task being measured (several opportunities for occlusion given a front facing camera system).

To characterize the direction and shape of performance features sampled over the course of training, regression models were fit to data that was sampled “continuously”. Kinematic features measured on the pre-test, four training monitoring meetings and post-test were represented as days 0, 6, 9, 12, 15, and 16. For each feature measured over time, a linear model was fit to the data and evaluated using the lack-of-fit-test to compare the residual sum of squares. The data was then evaluated to determine if a non-linear regression model was more suitable by adding a higher order term (highest explored was cubic). The likelihood ratio test was then used to compare models (e.g. quadratic versus linear) and if statistically different, the model with less residual sum of squares was accepted as a better fit for the data. Both the F-statistic (result of the lack-of-fit test) and model comparisons using the likelihood ratio test were set to $p < 0.05$ thresholds.

Finally, potential correlations between kinematics and clinical scores, and kinematics and therapist ratings were explored by calculating the Pearson correlation coefficient, with a significance threshold set to $p < 0.05$. Results of the correlation analysis are used to better understand the relationship between the system's characterization of performance (kinematics) and the therapist's assessment, both using validated clinical assessments and custom non-validated measures (ratings of both overall performance and individual performance components) developed for the purposes of this study. Average values of each measure were compared.

Note regarding why raw kinematic features were not rescaled: Kinematic features were left as raw measures for all analysis, although previous efforts by the AMRR team were undertaken to convert raw kinematic measures into meaningful assessment scales to assess a reach and grasp task. The Kinematic impairment index (KIM) (Chen et al., 2011) was developed to rescale kinematic features that vary in range and dimension (e.g. mm, m/s, angle) to a 0 to 1 scale, where 1 indicates maximum impairment. Rescaling was based on age-matched, non-impaired data and a range of stroke participant data in order to take into account both the acceptable range of non-impaired deviation, and the manner in which clinical observations of impairment correspond to raw measures. While the KIM allows for the combination of multiple rescaled kinematic feature measures to create a composite measure that aligns well with clinical observations, approaches such as the KIM rely on a control sample that demonstrates a fairly narrow normal distribution with low variability around a mean, as well as a stroke population fairly well distributed from mild to severe. The complex tasks such as those trained in the home-based AMRR study, however, yield less uniform non-impaired movement distributions with increased variance relative to simple tasks. Furthermore the participants within the home-based AMRR study demonstrated a more narrow range of impairment relative to those who participated in the clinical AMRR group (see Table 11 for the number of participants reflecting different impairment levels within each study); and for several of the participants within the home-based AMRR study, the baseline impairment of several features fell within non-impaired ranges measured from the control. Thus rescaling in a manner like the KIM is difficult to achieve given the lack of uniform

‘ideal’ movement. Increased variance may also be due to less robust methods for data collection that were explored in the home-based AMRR study relative to the clinical AMRR study, which include a large reduction of sensing infrastructure and sensors capturing movement, and the performance of tasks without the supervision of a therapist to ensure capture was without hindrance, both of which contribute to noisier data.

Results. Training with the HAMRR system led to significant changes in clinical outcomes assessing functional ability and motor function, but not all changes were maintained at the one-month follow up. Table 5 lists the clinical outcome measures evaluated before the beginning (pre), immediately following (post) and one month following (1 mo. follow-up) training with the HAMRR system. At the conclusion of the 5 weeks of training, significant improvement was measured for the Fugl-Meyer Assessment (FMA) and for the Wolf Motor Functional Assessment Score (WMFT-FA). At the one-month follow-up, changes were only maintained for the FMA. P-values < 0.1 were marked as trending towards change for the Wolf Motor Function Test Total Time measure for the affected limb. While MAL scores improve for most participants between the pre and post-tests, no significant or trending group-level change was measured for the Motor Activity Log (MAL).

Raw kinematic-based measures of movement quality did not show significant improvements at the group level. Results are presented in Table 6.

Table 5

Clinical outcomes measured pre, post, and one month following the HAMRR study

ID	Pre FMA (/66)	Post FMA (/66)	1 mo. FMA (/66)	Pre WMFT-FA (/5)	Post WMFT-FA (/5)	1 mo. WMFT-FA (/5)	Pre WMFT-TT (s)	Post WMFT-TT (s)	1 mo. WMFT-TT (s)	Pre MAL (/5)	Post MAL (/5)	1 mo. MAL (/5)
1	37	42	44	3.73	3.93	3.93	47.40	42.86	43.08	3.64	3.07	3.32
2	50	58	57	3.67	3.87	3.80	59.10	47.10	44.08	2.44	3.02	2.96
3	47	56	62	3.93	4.47	4.73	41.34	37.51	36.86	4.38	4.71	4.41
4	47	52	55	4.60	4.80	4.87	26.61	26.98	23.79	3.88	3.63	4.04
5	44	50	46	4.33	4.87	4.20	32.26	31.66	32.54	2.48	2.96	3.15
6	37	43	NA	3.50	3.40	NA	246.87	117.23	NA	2.96	3.50	NA
7	30	34	32	2.73	2.93	3.07	692.75	590.76	576.82	1.18	2.43	2.73
8	29	32	29	2.73	2.87	2.80	986.46	917.15	973.74	0.98	1.13	1.13
tValue		8.205	3.050		3.215	2.191		-2.167	-1.404		1.600	1.721
pValue		0.000*	0.023*		0.015*	0.071^{t}		0.067^{t}	0.210		0.154	0.135

Results based on a t-test for two dependent means, using a two-tailed hypothesis.

*$p < 0.05$ denotes significant change, $^{t}p < 0.1$ denotes trending change.

Subject 6 was unavailable for the follow up measurements.

Table 6

P-values for group level changes of kinematics following home-based AMRR training

Task A	f2	f3	f4	f5	f6	f7	f8	
Pre vs. Post	0.5484	0.0535	0.0524	0.1267	0.1773	0.8492	0.3076	
Pre vs. Follow-up	0.3161	0.2548	0.1459	0.5874	0.3753	0.3910	0.3881	
Task B	f5	f6	f8	f9	f10			
Pre vs. Post	0.5327	0.3904	0.1888	0.1608	0.3526			
Pre vs. Follow-up	0.3143	0.5038	0.2920	0.0756	0.6023			
Task C	f5	f6	f8	f9	f10			
Pre vs. Post	0.7561	0.6215	0.4932	0.0853	0.9756			
Pre vs. Follow-up	0.4790	0.1173	0.2274	0.3632	0.3158			
Task F	f4	f6	f8	f13	f14	f15	f16	f17
Pre vs. Post	0.8239	0.7813	0.1410	0.2281	0.1459	0.1834	0.5082	0.0878
Pre vs. Follow-up	0.2110	0.3259	0.3234	0.7085	0.1824	0.2317	0.5066	0.2572

Tables 7-8 display within participant percentage change between the pre and post-tests for all kinematic features measured (excluding the key-turn). Participants are primarily ordered (form left to right) in terms of WMFT FAS score and secondarily ordered by FMA score (with the exception of Subject 2). An indication of a participant's lack of *initial* movement quality impairment with respect to a kinematic feature is also indicated, where a 'C' denotes that the starting mean for a feature measured at the pre-test overlapped with age-matched non-impaired (control) ranges (range refers to mean plus one standard deviation). The presence of a dark-shaded diamond indicates that the standard deviation decreased across a favorable change between pre and post-tests, while a light-shaded diamond indicates the standard deviation decreased across an unfavorable change. Last Tables 7-8 indicates the direction (color) and shape (linear, quadratic, cubic) of a regression model that significantly fits the data. For the cone this trend samples from the pre-test, through four training monitoring meetings, until the posttest. For the transport over barrier the analogous tasks measured during training monitoring meetings (transport up and transport down) are provided (trends only fit to training monitoring sessions).

Mildly impaired Subjects 3, 4, and 5 have the highest FMA and WMFT FAS starting measures (WMFT average FAS => ~ 4 and FMA >= 44) and demonstrate the most extensive overlap with non-impaired ranges of kinematic data. Overall these participants demonstrate inconsistent changes in kinematic features in both favorable and unfavorable direction and most changes are designated as orange or blue, which indicates less confidence of true change given

the post-test mean overlaps within one standard deviation of the pre-test mean. Overall these participants demonstrate a reduction in standard deviation across several features but to a larger degree for features changing in favorable directions than unfavorable.

Mildly impaired Subjects 1 and 2 (initial WMFT < 4), one mild-to-moderately impaired Subject 6 (initial WMFT < 3.5 and FM < 40), and one moderately impaired Subject 7 (initial WMFT < 3.0 and FM < 35) show improvement in several kinematic-based measures of movement quality. Participants that are closer to moderate impairment appear to achieve more gains in lower level kinematic parameters, as measured in the cone task, in comparison to more high level kinematic-based parameters as measured in the transport tasks. For example compare the higher frequency of green boxes for Subjects 7 and 6 compared to Subjects 2 and 1 for the cone task. Subjects 6, 2, and 1 experienced the most consistent improvements in higher-level features measured for the transport task. Most decreases in variance are associated with favorable changes.

The remaining moderately impaired Subject 8 had few changes, although several of the cone features do begin to show indication of favorable improvement with most of those features also decreasing in variance. Several results for participant 8 were also missing data due to the inability to collect enough samples or analyze the transport data.

Tables 7-8 list the shape and direction of significant trends (if one could be fit) to data sampled between percentage changes marked in red or green only, in which the post-test mean did not overlap within one standard deviation of the pre-test mean. Most trends were linear in shape, while some trends were quadratic or cubic, across all subjects. Trends were fit to the cone data sampled across 6 time points (Pre, TM1-TM4, Post) and for the transport up/down, which were only sampled across 4 time points (TM1-TM4). Transport tasks trends for D and E are listed with their respective pre/post task correlates B and C, as these pairs share the same initial location of the target and could potentially engage similar joint spaces. No other patterns among trends is evident aside from that Subject 6, who experienced gains in both low and high level features, also had the greatest number of significant trends.

Table 7

Percentage change in kinematics for Moderate and Lower Function Mild Subjects

		Subject 8				Subject 7				Subject 6				Subject 2				Subject 1			
	WMFT FA:	2.73				2.73				3.5				3.67				3.73			
	FMA:	29				30				37				50				37			
		C	Δ	σ	Trend	C	Δ	σ	Trend	C	Δ	σ	Trend	C	Δ	σ	Trend	C	Δ	σ	Trend
CONE	***F***																				
time until 5% speed	**f4**		-11.47%	◆			**20.35%**				**-52.84%**	◆	Quadratic		-10.84%	◆			2.56%		
additional phase #	**f6**		-9.40%	◆			**34.69%**		Cubic		**-80.00%**	◆	Linear		-46.00%	◆			54.55%		
torso movement sum	**f8**		NA				**-60.21%**	◆	Linear		**-67.31%**	◆	Cubic		**-53.97%**	◆	Linear		**-45.23%**	◆	Quadratic
max horizontal error	**f13**		-8.40%	◆			**-46.34%**	◆	Quadratic		-23.69%			C	-22.31%	◆		C	**30.20%**		
max vertical error	**f14**		**-62.06%**				**-41.86%**	◆			**-39.25%**	◆	Linear	C	19.4425	◆			-24.73%	◆	
max speed	**f15**		3.98%			C				C	**14.09%**	◆		C	-1.26%	◆		C	-6.30%	◆	
bellness norm. area	**f16**		12.50%				-7.07%				**-59.24%**		Linear		-55.34%	◆			-8.80%	◆	
jerkiness	**f17**	C	-18.30%	◆			**-43.53%**	◆	Linear		**-43.60%**		Cubic	C	-14.02%	◆		C	23.15%	◆	
TRANS BARR FWD	***B***				D Trend				D Trend				D Trend				D Trend				D Trend
path ratio	**f5**		NA		NA		2.77%	◆	NA		NA		Linear		**-8.43%**	◆			1.66%		Linear
additional phase #	**f6**		NA		NA		17.65%		NA		NA				**-53.85%**						
total time	**f10**		NA		NA		4.65%	◆	NA		NA				**-25.70%**				**-14.65%**		Linear
torso movement sum	**f8**		NA		NA		**-39.56%**	◆	NA		NA				**-41.05%**	◆			**-54.33%**	◆	
TRANS BARR REV	***C***				E Trend				E Trend				E Trend				E Trend				E Trend
path ratio	**f5**		8.54%	◆	NA		-5.06%	◆	NA		**-6.92%**	◆	Linear		**-3.81%**	◆			-1.39%	◆	
additional phase #	**f6**		**48.15%**		NA		**-39.02%**		NA		-35.17%	◆			.4 to 0	◆			-44.44%	◆	
total time	**f10**		**78.19%**		NA		**27.63%**		NA		**-45.85%**	◆	Linear		**-14.58%**	◆			**-21.07%**		
torso movement sum	**f8**		NA		NA				NA		**-57.60%**	◆	Linear		**-33.01%**	◆			**-72.03%**	◆	Linear

% worsen **% improve** Red or Green denote no overlap between post-test mean and one standard deviation of pre-test mean

% worsen % improve Blue and orange denote there was overlap between post-test mean and one standard deviation of pre-test mean
Only changes >5% were highlighted

C Pre-test value falls within non-impaired range

◆ Standard deviation decreases for favorable change

◆ Standard deviation decreases for an unfavorable change

NA not enough samples to evaluate or no data collected

Table 8

Percentage change in kinematics for Higher Function Mild Subjects

		Subject 3				Subject 5				Subject 4			
	WMFT FA:	3.93				4.33				4.6			
	FMA:	47				44				47			
		C	Δ	σ	Trend	C	Δ	σ	Trend	C	Δ	σ	Trend
CONE	***F***												
time until 5% speed	f4	C	**9.77%**	◆	Quadratic	C	9.87%	◆		C	NA-Ex		
additional phase #	f6	C	-20%	◆		C	from 0 to 1			C	.2 to .4		
torso movement sum	f8		-12.48%	◆			**-29.36%**	◆		C	10.71%	◆	
max horizontal error	f13	C	7.94%			C	-11.47%	◆		C	12.67%		
max vertical error	f14	C	-7.10%	◆		C	12.17%	◆			-9.21%	◆	
max speed	f15	C	**-11.82%**	◆	Quadratic	C	**-13.22%**	◆	Cubic	C	NA-Ex		
bellness norm. area	f16	C	17.97%			C	from 0 to .			C	.01 to .03		Cubic
jerkiness	f17	C	**-35.12%**	◆	Quadratic	C	-9.84%			C	NA-Ex		
TRANS BARR FWD	***B***				D Trend				D Trend				D Trend
path ratio	f5	C	**3.72%**	◆		C	-1.19%			C	**7.65%**	◆	
additional phase #	f6	C	100%			C				C			
total time	f10		-8.07%	◆		C	6.60%			C	**-30.06%**	◆	Quadratic
torso movement sum	f8		**-26.50%**	◆			-16.67%	◆	Linear		-47.69%	◆	
TRANS BARR REV	***C***				E Trend				E Trend				E Trend
path ratio	f5	C	**6.67%**			C	-1.07%	◆			**9.12%**		
additional phase #	f6		-50%	◆		C	om .2 to 0	◆		C	Zero to .2		
total time	f10	C	-1.09%	◆		C	7.55%	◆		C	**12.60%**	◆	
torso movement sum	f8		-23.03%	◆			**-56.67%**	◆		C	**-61.89%**	◆	

% worsen **% improve** Red or Green denote no overlap between post-test mean and one standard deviation of pre-test mean

% worsen % improve Blue and orange denote there was overlap between post-test mean and one standard deviation of pre-test mean
Only changes >5% were highlighted

C Pre-test value falls within non-impaired range

◆ Standard deviation decreases for favorable change

◆ Standard deviation decreases for an unfavorable change

NA not enough samples to evaluate or no data collected
NA-Ex data thrown out due to participant reaching as fast as possible (did not understand directions)

Table 9 displays the Pearson correlation coefficient and corresponding p-value between pairs of kinematic features and clinical scores measured on the pre-test. Table 9 also displays the results of comparisons between pairs of *changes* in kinematic features and *changes* in clinical scores measured between the pre and post-tests. With the exception of kinematic comparisons to the MAL and some comparisons to Task B path ratio, overall high correlations (Pearson correlation coefficients (R^2) greater than 0.7 and 0.8) were found between the clinical scores and kinematic measures from the pre-test, while almost no significant correlations were found between changes in scores. Correlations between the cone Task F and clinical scores were not explored; previous work does confirm correlation between *combinations* of low-level features in the KIM (Chen et al., 2011) extracted from repetitive cone reaches and the WMFT FAS clinical scores.

Table 10 displays the Pearson correlation coefficient and corresponding p-value between pairs of kinematic features and therapist ratings. Therapist ratings were ordinal ratings assigned to individual reaches by therapists who watched videos from the training monitoring sessions; rating criteria can be found in Appendix A. For cone Task F, highest correlations were found between therapist ratings and reach time, speed phases, normalized area, and torso movement. Features measured from the transport tasks show highest correlations with reach time, speed phases, and torso movement with only some less correlation with path ratio, most evident in Task E. Total time for these tasks was provided for the therapist in the iPad application as a % of maximum allowable time to complete the task as means to help assess the timing. Therapist ratings for transport, followed by release, showed the least correlation with individual kinematics, while the therapist ratings for initial overall impression (adapted from the WMFT FAS) seemed to have the highest correlation across tasks. Overall ratings for the transport tasks show *somewhat* less strong correlation with features common to the cone than those measured for the cone task, demonstrated by the presence of slightly more of the darkest shading present in the first section of the table for the cone.

Table 9
Correlations between kinematics and clinical scores

		Torso Movement		Total Time		Speed Phases		Path Ratio	
		R^2	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**
Task B Pre-Test	MAL	-0.724	0.066	-0.855	0.007	-0.883	0.004	-0.683	0.062
	FMA	-0.789	0.035	-0.795	0.018	-0.761	0.028	-0.697	0.055
	WMFT TT	0.945	0.001	0.955	0.000	0.966	0.000	0.891	0.003
	WMFT FAS	-0.825	0.022	-0.946	0.000	-0.903	0.002	-0.751	0.032
Task B Change	MAL	-0.582	0.226	0.478	0.338	0.282	0.588	-0.291	0.576
	FMA	0.605	0.204	-0.427	0.399	-0.572	0.236	-0.432	0.393
	WMFT TT	0.970	0.001	-0.564	0.244	-0.638	0.173	-0.097	0.855
	WMFT FAS	0.416	0.411	0.404	0.427	0.093	0.860	0.038	0.944
Task C Pre-Test	MAL	-0.732	0.062	-0.825	0.012	-0.773	0.024	-0.792	0.019
	FMA	-0.812	0.026	-0.804	0.016	-0.897	0.003	-0.924	0.001
	WMFT TT	0.967	0.000	0.850	0.008	0.928	0.001	0.960	0.000
	WMFT FAS	-0.830	0.021	-0.951	0.000	-0.918	0.001	-0.881	0.004
Task C Change	MAL	0.414	0.414	-0.344	0.404	-0.477	0.233	-0.509	0.197
	FMA	0.503	0.310	-0.360	0.381	-0.244	0.560	-0.179	0.672
	WMFT TT	0.451	0.369	0.166	0.695	0.179	0.672	0.418	0.303
	WMFT FAS	0.514	0.297	0.098	0.818	-0.043	0.919	0.285	0.494

KEY **R^2** ≥ 0.8 ≥ 0.7

Table 10

Correlations between kinematics and ratings

		Time Til 5% Sp Max		Max Horizontal Error		Max Vertical Error		Speed Phases		Peak Speed		Normalized Area		Jerkiness		Torso Movement Sum	
		R^2	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**
	initial overall	-0.841	0.000	-0.626	0.000	-0.547	0.001	-0.891	0.000	0.671	0.000	-0.906	0.000	-0.565	0.001	-0.877	0.000
	trajectory	-0.801	0.000	-0.414	0.021	-0.373	0.039	-0.821	0.000	0.630	0.000	-0.827	0.000	-0.368	0.042	-0.732	0.000
	compensation	-0.884	0.000	-0.646	0.000	-0.552	0.001	-0.906	0.000	0.646	0.000	-0.850	0.000	-0.390	0.030	-0.947	0.000
Task F	**manipulation**	-0.875	0.000		0.001	-0.638	0.000	-0.921	0.000	0.639	0.000	-0.914	0.000	-0.494	0.005	-0.924	0.000
	transport	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	release	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	final overall	-0.842	0.000	-0.622	0.000	-0.560	0.001	-0.894	0.000	0.659	0.000	-0.913	0.000	-0.574	0.001	-0.876	0.000

		Total Time		Path Ratio		Speed Phases		Torso Movement Sum	
		R^2	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**
	initial overall	-0.851	0.000	-0.755	0.000	-0.844	0.000	-0.859	0.000
	trajectory	-0.691	0.000	-0.361	0.059	-0.602	0.001	-0.707	0.000
	compensation	-0.957	0.000	-0.733	0.000	-0.914	0.000	-0.918	0.000
Task D	**manipulation**	-0.791	0.000	-0.711	0.000	-0.776	0.000	-0.757	0.000
	transport	-0.463	0.013	-0.367	0.055	-0.418	0.027	-0.515	0.005
	release	-0.665	0.000	-0.400	0.035	-0.621	0.000	-0.642	0.000
	final overall	-0.851	0.000	-0.755	0.000	-0.844	0.000	-0.859	0.000

		Total Time		Path Ratio		Speed Phases		Torso Movement Sum	
		R^2	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**	**R^2**	**pVal**
	initial overall	-0.774	0.000	-0.591	0.001	-0.758	0.000	-0.754	0.000
	trajectory	-0.717	0.000	-0.445	0.018	-0.699	0.000	-0.642	0.000
	compensation	-0.852	0.000	-0.722	0.000	-0.875	0.000	-0.842	0.000
Task E	**manipulation**	-0.744	0.000	-0.781	0.000	-0.696	0.000	-0.807	0.000
	transport	-0.589	0.001	-0.478	0.010	-0.563	0.002	-0.634	0.000
	release	-0.613	0.001	-0.660	0.000	-0.604	0.001	-0.744	0.000
	final overall	-0.774	0.000	-0.591	0.001	-0.758	0.000	-0.754	0.000

KEY R^2 ≥ 0.8 ≥ 0.7 ≥ 0.6

Discussion. The design of the home-based AMRR system focused on training participants to confidently perform functional tasks such as a transport task. Results support that unsupervised INR training can induce functional improvement, demonstrated by changes in the WMFT functional assessment score, and motor function, as measured by the FM Assessment.

While trending towards improvement, the lack of significant change in the WMFT total time measure may have resulted from other changes in quality of movement. Training with the HAMRR system focuses on multiple aspects of movement performance including spatial accuracy, which may contribute to reduced speeds. More training beyond 15 sessions across the duration of 5 weeks could also potentially push trending improvements towards significant change and may be required for the retention of any improvements measured in the post test at the current intensity level of training.

Lack of significant change measured in the MAL could result from lack of translation into everyday tasks as measured by the MAL. While HAMRR training aimed to improve confidence in using the affected limb in independent contexts, the reduced amount of the therapist intervention and confirmation of gains could potentially affect a participant's ability to self-assess the extent of his improvements or how to translate his training into everyday activities, considering the MAL alone. Other explorative measures of participants increasing activity outside of training are discussed later in the questionnaire response section. Among the 8 participants, Subject 1 reported personal issues that led to emotional distress and may have confounded his self-assessment. Removal of Subject 1's MAL score from the group would result in significant change among the remaining 7 participants, suggesting that as a subgroup the remaining 7 participants experienced change that was at a minimum trending towards improvements in the MAL.

Ultimately to better connect with activities of daily living training likely needs to cater to the activities that are considered meaningful to participants. Customization of training may need to be extended both in terms of type of tasks as well as training sensitivity and sequences.

Training led to no group-level changes in terms of movement quality, which is likely a result of 5/8 participants being only mildly impaired, coupled with training at a fixed dosage,

sequence, and physical setup (The chair could be moved backwards/forwards to preset locations but the target objects were fixed; thus some participants could achieve task completion without being sufficiently challenged in terms of extending their arms). Mild impairment with fixed training likely results in a reduced opportunity for improvement (or 'floor' effect) given that participants are already starting at low impairment, and the system was not adapted to make training more challenging and thus trigger feedback to promote changes in movement.

When participants are evaluated on an individual basis, results demonstrate that those who are within a range of ability, centered around mild-moderate impairment standing, experienced improvement across several features, as indicated in Table 7. The results of these participants show promise that the feedback and training was working for participants who had room to improve their movement quality given fixed training. Furthermore, these results suggest that adaptable training (e.g. increasing sensitivity for those participants who were high functioning, altering the physical space as necessary by varying target locations based on participants' extension abilities) could potentially have pushed other participants to more improvement, and potentially resulted in group-level change.

Trends in training further support that pre, post changes for which statistical analysis is not applicable are supported by cumulative improvement for several of the observable training dynamics (i.e. for those tasks sampled continuously like the cone). Trends exhibit no patterns in linear versus non-linear across features or subjects; but differences in trend shape support that people respond differently given fixed path training, e.g. some people could have benefited from longer training or higher intensity. Each patient has different kinematic challenges and different improvement distributions. Individual improvements follow trends/slopes that have different shapes/fits thus potentially denoting different effects/impacts of fixed paths for each subject. People respond differently to training based on the shapes of the regressions. If we had adapted to each persons needs we likely could have stylized this over time.

While one would have expected moderately participant to also benefit from training, as previously mentioned, the HAMRR hardware set up was not adequate/could not be adapted

adequately to capture kinematics accurately and implement training protocol accurately, given the particular set of impairments Subject 8 faced. This is especially true for complex tasks that fell outside the current ability of this subject. Also Subject 1's personal issues unrelated to the study likely influenced his performance (e.g. in addition to emotional distress, the subject often reported being very tired from having to pack and move himself to another apartment) especially on the day of the post-test. The emotional and physical effects may explain his inconsistent improvement in kinematics (and decrease in MAL as previously mentioned).

Correlation analyses suggest that the high-level measures of kinematic impairment used to evaluate the transport tasks do correspond to initial impairment as measured by the therapist. However the lack of correlation between changes in clinical scores versus changes in kinematics suggests that while training led to functional improvement it was not catered towards stylizing movement. One limitation of this correlation analysis is that individual features are being compared to clinical scores that are composite in nature. Combining kinematic scores in an informed way may be more appropriate for comparing between kinematic assessments and clinical scores.

Features that show highest correlation with the therapist ratings may be stronger in terms of their visual manifestation in the side perspective of the video. Trajectory error and peak speed are features the system measured that may not have been noticed by the therapist or were difficult to visually discern from the profile perspective of the video. Overall spatial measures such as trajectory error and path ratio are somewhat correlated to therapist ratings but not as highly. Differences in spatial assessment may present cases in which detail caught by system is not visually tracked by therapist ratings (e.g. kinematics show trends of improvement while ratings are constant), and vice versa, (e.g. the system does not track features such as manipulation or elbow joint extension). Increases in speed, which is often not discouraged by therapists, in some cases can be penalized by the system if the magnitude exceeds a set threshold. This difference could also explain a lack of correlation between the system's assessment and the therapist's observations.

Collectively Tables 9 and 10 support the utility of a hybrid approach (integrating therapist observation with kinematic and computational evaluations) to adjusting and tracking therapy, which can provide a more informed picture of the nature of recovery. Validated means for therapist assessment are catered towards the overall performance of tasks (ranging from simple to complex), and the presence or absence of more apparent individual aspects of movement. Kinematics-based assessments specify the precise magnitude of deviation from non-impaired movement patterns, whether they are visually prominent or not, and thus can potentially reveal the individualized nature in which different aspects of performance are affected by training for different participants.

Summary of participant responses to questionnaire. Results of system experience questionnaires for all subjects are included in Appendix B. This custom questionnaire while non-validated was designed to provide insight into the dynamics of participant experience as they are sampled before every third session of independent training.

Acceptance of the system but lack of challenge. Overall subjects reported that the therapy amount (number and duration of sessions) was about right. Exceptions include Subject 2, who throughout training thought therapy was less than enough, and Subject 5, who reported training was too little by the third week but then returned to reporting it was about right.

Subjects reported that challenge level was easy, with the exception of Subject 8 who consistently thought training was somewhat difficult. Insufficient challenge reported by most subjects support that the lack of consistent change among kinematic measures could to some extent be related to lack of adaptation of the system.

Overall participants liked using the system to some degree, where Subjects 1 and 2 increased their enjoyment over time while Subject 8 decreased over time. Directions were perceived as somewhat, to very easy to understand, however in the free response several participants reported that directions were excessive and repetitive. Subjects 3 and 4 had the most fluctuation with respect to the ease of understanding directions but never dropped below ‘neither easy nor difficult’.

All participants thought both the visual and sound feedback were easy to understand in terms of communicating performance, with the exception of Subject 8, who consistently found both the sound and visual feedback somewhat difficult to understand performance. While all participants reported liking the visual feedback to some degree, Subject 8 somewhat disliked it. For the most part all subjects reported liking the audio feedback to some degree, with the exception of Subject 4 neither liking nor disliking the audio feedback for the second half of training. Overall subject 8's self-reported difficulty with the system aligns with our observations that training needed more adjustment to suit her needs. Thus the system should not only be able to increase challenge level for mild participants but also modify training for more impaired participants as well. Participant 8 also suffered from visual impairment, which decreased her ability to independently analyze images for some of her training.

Several participants reported using their arm more than usual outside of training for anywhere from one week to all weeks (any participant who reports using his arm 'about the same' reports by the last session that arm use was 'somewhat more than usual'). The exception is Subject 7 who consistently reports using his arm the same as usual. About half the subjects reported feeling less tired than when starting training, while Subject 8 reported feeling somewhat more tired for the last 2 weeks. With the exception of Subject 3, whose mood stayed the same, all participants felt as though their mood improved after training.

Participant responses demonstrating increased awareness and confidence outside of therapy. Several free response answers from participants suggest that they have increased using their arm outside of training, and/or provide insight into how the participant is self-assessing their progress.

Subject 2 consistently reported using his affected arm somewhat more than usual, feeling somewhat better than usual, and with somewhat more energy after training. Subject 2 explained: "On day one, 100 sounded like a lot of reps, but I am not tired after a session and feel like I can do more. Feels like arm movements are the same or slightly better at end of sessions, no worse." Overall his self-perception of his progress was that he was doing "good"; he reported feeling like

he was doing well: because “of the training sessions, I am doing more at home with my exercises.” Despite not being challenged enough given he found the training very easy, he says he has become “more aware of using (his) right arm more outside of training...that is the biggest thing I got out of the training.” Subject 6, who was only able to answer questionnaires the first 2 weeks due to scheduling, reported that he felt it was “Very inspiring to continue in my progress to get better in moving my limbs”. Both of these participants were also most successful in achieving improved movement quality across several aspects of movement.

Subject 4, who was among the highest functioning participant, was concerned about ‘being a good subject’ since his performance rarely triggered negative feedback. However by the final session he expressed feeling more challenged than he reported before, which gives him the opportunity to “see just how much progress I have made. A lot of this stuff when I first had my stroke I couldn't have done.” Subject 5, who was also among the highest functioning participants, said training “would have been more challenging” had he participated right after his stroke, reiterating the system’s appropriateness for lower functioning participants. Subject 5 did report by week 4 that “I have been doing very well. I am trying to apply the things I have learned to my daily life.” And by week 5: “I am more concerned with how I reach for things now” and that he is “using (his) right hand to adjust radio while in the car. It's coming natural. I'm grabbing at things more readily as well.” Subject 5 also uses the visual feedback as an indication of his progress, reporting the third week that, “with the exception of the broken boat, I think I am doing well. Can't seem to get the boat right”, which is followed up 2 weeks later with a self-report that he is doing “Great. Spectacular. Getting better. Not seeing the broken boat”.

Subject 8, on the other hand, reported that she consistently had trouble utilizing both the visual and more complex audio feedback. Despite these challenges she reported that her mood actually somewhat improved after sessions for all weeks. The training “gives me things to think about…I have ideas of what I need to do at home.” Subject 8 reported using her arm slightly more than usual, such as “reaching for a doorknob and refrigerator door this week…purposefully using it (her hand) more.” She also “bought a standing tube from (the) dollar store to mimic practice at

home with the portable cone". Overall her self-perception of progress reflected that she is motivated but realistic in her expectations: "I think I have been doing ok, I know I cannot get it all." Session 2 was more difficult: "I don't think that I did well. It was difficult to complete the tasks so I didn't feel that I did that well." But finally in the last two sessions the participant felt she did "Great" and "good".

3.3 Conclusions and Summary of Outcomes

The clinical and home-based AMRR systems together have trained stroke survivors with a range of movement challenges and impairment levels primarily in the mild to moderate range (breakdown shown in Table 11). The home-based system targeted participants that are relatively higher functioning in comparison to the clinical system given the lack of supervision and current level of adaptability. Collectively results from the clinical and home-based AMRR systems demonstrate improved functionality and movement quality can be achieved using systems designed with a mixed discipline approach. While both training systems led to functional improvement as measured by the WMFT, the extent of movement quality improvement assuming a fixed timescale of training is likely most dependent upon the extent of adaptation, relative exposure to feedback providing explicit assistance on performance, and the ability level of the participant. A comparative summary of outcomes versus protocols is summarized in Table 12.

While the control group in the AMRR study, which used traditional means for therapy, also experienced improvements in the functional activity score of the WMFT, only the group that trained with the AMRR system also experienced consistent improvements in kinematic measures trained by the system in both trained and untrained tasks. Thus training with abstract feedback components (encoding the magnitude and direction of error of kinematic measures) allowed for improvements in both movement quality and functional assessment of untrained tasks measured in the WMFT (not directly connected to training).

In contrast to both the supervised control (traditional therapy) group and the experimental group who trained with the clinical AMRR system, training with the home-based AMRR system

with minimal supervision (~80% of training was unsupervised with exception of Subjects 7-8 who received slightly more supervision as needed) led to functional gains and yielded improvement in movement quality for only a subset of participants.

Unsupervised INR training that is highly customized to patient needs with options for continuous adaptation input by the therapist can potentially have the most impact on both movement quality improvement and functional recovery by spending a fixed amount of training time on the most critical issues of the participant. Because the clinical AMRR study has demonstrated integrated training is possible using an integrative feedback approach based on the form of the action (described in Chapter 5), this could likely lead to overall gains in multiple aspects of movement quality. Also slightly increasing the presence of the therapist, even if remotely administered, might have a powerful effect given that the therapist can provide high-level feedback on performance or provide strategies for using the feedback during training.

While supervised AMRR is able to induce highly consistent changes, unsupervised INR training, especially if done at the home, is likely better able to address higher-level outcomes such as long-term adherence to therapy, becoming an active driver of the recovery process, and improvement in complex tasks performance rather than improvements in details of movement quality because of infrastructure and supervision limitations.

Thus far these systems have been designed and tested for right side affected participants only, for the sake of evaluating a methodology and minimizing potential confounding variables from a more diverse population. However these systems can easily be generalized to left side affected participants from a strictly movement capture perspective. Other aspects of stroke impairment (e.g. cognitive or perceptual effects) that might be associated with left-side affected participants require testing in practice or screening to match the cognitive and/or perceptual criteria evaluated thus far to ensure the generalization of other aspects of the system beyond movement capture and analysis alone (e.g. use of instruction and feedback environments).

Table 11
Impairment levels of stroke survivors who have trained with AMRR

Incoming impairment	AMRR study participant count	HAMRR study participant count	Total
Mild	4	5	9
Mild Moderate	3	1	4
Moderate	1	2	3
Moderate Severe	2	NA	2
Severe	1	NA	1

Table 12
Summary of outcomes versus protocols

	Feedback approach	Supervised/Adapted in real-time	Functional gains in WMFT	Extent to which movement quality improved
Control (compared to AMRR only)	Traditional therapy	Yes	Yes	No significant change
AMRR	Low level, concurrent feedback	Yes	Yes	Group level
HAMRR	Mixed concurrent and summarized feedback	No	Yes	Impairment dependent

CHAPTER 4

INTERDISCIPLINARY DESIGN CONCEPTS FOR INR MEDIA

The following interdisciplinary design concepts are synthesized from prior work in INR, external but related disciplines and the systems designed by the MRR group at ASU that utilize a mixed discipline approach. Concepts presented provide generalized guidelines for designing media for INR based on specific application for upper extremity training for stroke but can potentially inform a number of interactive learning scenarios.

4.1 Concepts for Consideration per Media Component

4.1.1 Function: the media environment should vary from prescriptive to reflective. A media environment for INR should offer a range of functionality in which components of the feedback can fully instruct the participant on what to do (*prescriptive*), provide partial help (*assistive*), imply what the participant should consider (*suggestive*), or promote longer term contemplation (*reflective*). The exposure of feedback from each of these categories should help maximize engagement, while minimizing boredom and frustration by ensuring both the accumulation and sequence of feedback is appropriate.

Within the context of an interactive system, both prescriptive and assistive feedback should promote explicit information processing: the relationship between the patient's causal action and resultant feedback is direct and readily apparent, without contemplation and upon limited interaction. An example of assistive visual feedback in the AMRR system is the animated movement of an image to the right when the patient's hand deviates far right from an efficient reaching path (Figure 3). Suggestive or reflective media feedback should promote implicit information processing, in which understanding is achieved through exploration and self-discovery, often requiring multiple interactions with the feedback. An example of suggestive visual feedback in the HAMRR system is the display of a well formed versus broken boat in which the nature of the boat reflects overall spatial performance across five reaches (Figure 4). The majority of feedback on movement performance should fall within the assistive and suggestive categories,

while only offering minimal prescriptive feedback during training on complicated instructions (such as a video demonstrating the task). Highly reflective media should be reserved for understanding performance of tasks across multiple timescales (such as multiple videos assembled by the therapist to show progress). During interactive training, assistive feedback is most conducive to performance of individual aspects of movement while suggestive feedback is conducive to promoting understanding of relationships among components or performance across multiple timescales.

4.1.2 Representation: the media environment should vary from direct to abstract. Representation refers to the extent to which media represents the participant, his/her environment, and the task at hand. Direct representation aims to replicate as many aspects of the physical experience as possible, while abstract representation places the problem in a different context by using audio and/or visual metaphors to represent the participant's action and environment. In the context of representing performance during training, while direct representation can be very effective in prescriptive contexts such as providing a task instructional video, communicating performance information by using abstract representation is more conducive to facilitating motor learning during training. Providing a visual representation that does not directly reflect the participant can promote recontextualization (White, 1998). The use of abstract feedback can encourage active learning and problem solving by requiring the participant to determine the causality between his action and the corresponding change in feedback. For example, within the clinical AMRR system the formation of the image and musical phrase is tightly coupled to and directly controlled by a participant's action. The novel (non-familiar) feedback focuses the participant's attention on the form of the action, and can thus emphasize deviation from efficient performance, and provide intuitive, detailed direction for improvement (e.g. image particle stretch). Abstract feedback also supports generalization; because abstract media-based feedback does not reflect a specific situation grounded in physical reality, it can be applied to several different training scenarios. It should be noted that direct representational media which has meaning to the participant (e.g. photographs of the participant, friends and/or

family) can potentially both engage and motivate the participant in rehabilitation contexts, though this can be participant dependent. The recommendation provided by this interdisciplinary concept is that using direct representation of the participant and tasks to depict performance during or immediately following task completion may reduce the opportunity for active participation and recontextualization.

4.1.3 Participation: the media environment should balance passive consumption with active creation. Participation describes the extent to which the user affects the media he experiences, which can range from passive consumption as a spectator to sole creator. Media environments for INR should facilitate active participation, a balance between media creation and consumption to encourage active exploration but in a guided manner that will ultimately lead to meaningful discovery. Media content that promotes active learning through participation should therefore focus on underlying aspects of the experience and allow the user to reconstruct some of its aspects (e.g. the user discovers his movement is generating music, and more specifically, that his movement speed controls the rhythm). While training at times should allow for more open interpretation (which can be facilitated by using suggestive or reflective media), the feedback cannot be entirely exploratory if intended to address targeted challenges. The feedback must be able to balance open interpretation with passive consumption of assistive media to direct the experience when needed. Facilitating the participant's agency (e.g. how much control he has and his awareness of this control) as needed within an interactive environment can also increase empowerment, which is especially relevant in the context of relearning functional use of the arm following stroke, amidst physical or emotional challenges. Rich, creative experiences can empower the individual by placing these challenges in a different, more engaging and/or lower-risk context. While independent discovery should be maximized when possible, intervention from the physical therapist can play a critical role in monitoring how the patient is responding to challenges and helping the patient gradually understand how to utilize the media. As proficiency increases, the amount of challenge and potential for self-discovery should expand. If challenge

becomes too great, challenge should decrease to ensure that empowerment is not undermined or lost.

4.1.4 Multimodality: the media environment should utilize the most appropriate modality based on the movement component and combine modalities to communicate relationships among components. The most appropriate modality should be utilized depending upon sensory modality appropriateness, feedback semantics, and type of monitoring required. Different senses are suited for processing different types of information most accurately. As previously discussed in prior work, visuals are best suited for spatial information while audio information is best suited for timing information. Different types of movement also require different types of monitoring while performing a task (Wulf & Prinz, 2001): while audio or visual media can be effective in communicating distal aspects of movement that require continuous monitoring such as movement of the endpoint (hand), audio feedback is best suited for temporary alert signals pertaining to more proximal aspects of movement that should not be continuously monitored (e.g. shoulder-lifting). Visual information is also conducive to summarizing information in detail over time and space when magnitude and direction are important. Finally in terms of organizing the overall structure of the feedback into a narrative, more explicit content can be communicated by the visuals (e.g. goal of traveling on a boat in the HAMRR system) while implicit content is best communicated in music (e.g. music provides a narrative mood within the HAMRR system).

4.1.5 Multistream: the media environment should range from single to multiple streams to vary training complexity and facilitate relationships among training components. A media stream is a single and sometimes continuous flow of information provided in response to a participant's input. A stream is often mapped to a single movement component (e.g. in the AMRR system, musical rhythm is mapped to hand speed, image pixilation is mapped to hand distance to target). The principle of multimodality can be used to efficiently communicate multiple streams of information simultaneously to facilitate better understanding of the relationship between spatial and timing aspects of movement (e.g. receiving information on progression to the target in terms of time and space can help understanding of velocity). Multiple (redundant) media streams also

can be mapped to a single component to emphasize its importance in the movement hierarchy with respect to completing a functional task (e.g. within the AMRR system, both harmonic progression and image pixilation are mapped to distance to target). However each feedback component is only used once (e.g. horn sound for torso will not be used for any other movement component). Designing media in terms of stream per movement component allows for modular training that can easily build or reduce in complexity. Assistive media is typically single stream while more complex mediated experiences often utilize multiple media streams (e.g. suggestive feedback provided as a narrative scene using color for error magnitude and shape for direction error, to describe overall performance across a set of five reaches).

4.1.6 Time delivery and usage goal: the timescale at which feedback is given should vary based on relevance to performance and desired amount of self-evaluation. Concurrent feedback (Cirstea & Levin 2007; Timmermans et al, 2009) is provided in real-time, or exhibiting no perceptible delay, with respect to the participant performing an action. Aspects of movement that are continuously monitored by the mover while performing an action, such as end-point spatial progress towards a target (Sarlegna & Sainburg, 2009), may require continuously delivered concurrent feedback for detailed knowledge to correct error. Aspects of movement irregularly relevant to performance of a specific action (Wulf & Prinz, 2001), such as torso compensation during a reaching activity, are more appropriately described by intermittent feedback so as to not interfere with the continuous monitoring of the end effector. Intermittent feedback in this context is concurrent feedback that is both limited in the amount of information given, such as on/off feedback, and is provided only when relevant to performance (e.g., a brief audio indicator provided when torso compensation occurs). Feedback provided offline can afford the participant the opportunity to self-assess. Offline feedback can be terminal, immediately following an action; delayed, following an action after an interval of time; or summary/aggregate, provided after multiple actions are completed. While increasing the period of time between action(s) and feedback increases the opportunity for self-evaluation, it is important to consider how the semantics of feedback should change based on the time delivery structure.

While an action is being performed, motor behaviors may occur along a continuum ranging from application of external information for real-time correction, to reliance on internal models only (Seidler et al., 2004). Accordingly, feedback can provide information for different usage goals: *online* application (modification of ongoing performance); it can primarily facilitate *feedforward* planning of future movements; or it may provide weighted combinations of both. Feedback components should be constructed in a manner that promotes the most appropriate usage strategy by the participant. *Continuous*, *visual* feedback, for example, often allows for *online* adjustment of action due to its ability to *explicitly* communicate direction for improvement in *real-time*. On the other hand, the human brain's strong memory for musical constructs promotes the efficacy of *audio* media as a powerful feedforward tool for movement planning (Levitin, 2006; McAdams & Bigand, 1993). Audio perception also affords the opportunity for more *implicit* discovery given that experience aggregates statistically, allowing for the learner to independently detect regularities or patterns in transitions states within the music. Although the interactions of music and movement can be complex, the majority of music-assisted movement learning occurs implicitly and subconsciously, similar to the intuitive learning of dance (Levitin, 2006; Jaques-Dalcroze, 2007).

4.2 Concepts for Connecting Experience

4.2.1 Multileveled: media environment should vary in terms of both meaning and time delivery based on the complexity of the experience to help stimulate self evaluation. Learning in everyday contexts, such as learning to ride a bike, is a mixture of both linear, causal interactions (e.g. pushing the pedal down advances the bike forward) and the accumulation of varied experiences (e.g. maintaining balance requires more extensive practice on different surfaces). Both examples contribute to knowledge of riding a bike yet the complexity of the actions, the timescale of practice, and the resultant feedback vary. Feedback on performance for INR should also be a mixture that varies in terms of both semantics (e.g. the meaning conveyed by the visual content) and structured time delivery to gradually stimulate the participant's self-evaluation of his activity performance across multiple levels of challenge. Feedback fading is a technique used

within motor learning contexts in which feedback is gradually reduced to prevent dependence (Schmidt, 1991). Traditional approaches to fading feedback are typically over the time dimension only, such as reducing the number of times a patient receives a verbal description on the quality of his performance. On the other hand two-dimensional fading changes the feedback over the time dimension and semantic dimension. The semantic dimension can range from feedback that is elemental in nature (e.g. color indicates magnitude of trajectory error) to inferential narrative (e.g. a scene within a story is a metaphor for overall trajectory performance across five reaches). In motor rehabilitation, multileveled media should facilitate the participant's understanding of movement in terms of both individual motor elements and their relationship to function. A reductive hierarchy is a compositional technique for structured learning that helps organize the design of multileveled feedback based on the complexity of the experience, in which low-level aspects of experience are detailed and easily discoverable; and more complex, high-level aspects of the experience are presented as abstracted summaries. All principles in the lowest level of media are manifested in the more complex media but are reduced in presence. For example in the home-based AMRR system, elemental aspects of the media (e.g. color, shape) are prominently used to explicitly communicate the magnitude and direction of trajectory error for a single reach, considered low-level training. In high-level training across a set of reaches, the feedback is provided in the context of a narrative metaphor (e.g. a broken boat with clashing color to demonstrate inefficient performance), holding consistent use of elemental media components but embedding them in a more complex multi-stream scene (Figure 4).

4.2.2 Aggregation: media environments should support the accumulation of multiple system interactions to contribute to a knowledge goal. Aggregation in this context refers to the accumulation of multiple system interactions to facilitate the formation of an internal model with respect to the knowledge goal. Media that supports aggregation adheres to the following criteria: (1) Feedback is modular in mapping. For example a single stream of feedback is mapped to a single movement element, and can be removed or added without affecting other components within the media environment. (2) The feedback is supportive of a variety of manifestations of the

problem: the same feedback environment is generalizable, or can be applied across multiple types of tasks (as is often supported by using abstract feedback). While not every feedback element will be present across all tasks based on task complexity (e.g. a reach to lift task requires an additional element on the lift component) the core aspects of the activity should be consistently expressed as predominant feedback across tasks (e.g. feedback mapped to hand speed and trajectory). (3) Every element of the feedback should contribute to the larger understanding of the knowledge goal. Each interaction needs to contribute to a larger "picture" revealed to the participant. If an element does not contribute to the functional task it should not be included as an interactive feedback component. By adhering to the three criteria above the media has a greater potential to support modular construction within multiple nonexclusive paths. For example two patients facing different challenges (e.g. compensation versus trajectory error) require different paths to forming a methodology for achieving unimpaired performance. Although both participants might experience different sequences of feedback both participants should improve towards unimpaired ideals with respect to multiple aspects of movement.

4.2.3 Form coherence with action: the overall structure of the feedback should be organized based on the action represented. Form coherence refers to the tight coupling and semantic congruence between the content of the media-based feedback and the action that generates the feedback. The goal of the action (e.g., successfully completing a reaching task) and the goal represented in the media (e.g., successfully completing a media-based goal) must be analogous. The relative contributions of movement components in achieving the action goal must be reflected in the relationship among the corresponding media elements. In addition to communicating performance, individual feedback streams must also encode the ideal form of their movement components (e.g., a smoothly executed musical feedback progression is generated by an efficient reaching movement) to allow for intuitive communication of error and direction for improvement. Both form integration and form coherence require that the media feedback reflect all key aspects of the entire action, rather than communicating single aspects of movement in isolation. An action representation for a goal-directed activity such as a reaching

task identifies the key movement components, and establishes overall interrelationships among their roles within the hierarchy of action goal completion. When designing media for stroke rehabilitation, form integration and coherence can be achieved by using the architecture of the action representation for structuring the media composition. Paralleling the structure of the activity within the media composition can create a coherent interactive experience for the participant. For example, in the AMRR system, the goal within the interactive media-based task (the completion of the image and musical progression) directly reflects the completion of the goal of the physical action (accomplishment of the reaching task). Activity-level kinematic parameters are mapped to continuous and prominent audio and visual media that contribute the most to completing the interactive task. Body function level measures are mapped to discrete visual and sonic indicators that can be toggled on or off. Prominent use of linear visual perspective and smoothly accelerating/decelerating music rhythms in the media encode key invariant elements of the movement (straight trajectory and bell-like speed curve, respectively). The tight coupling between media and action that results from form coherence allows the clinician to intuitively and continuously communicate to the participant the focus and structure of each stage of therapy by selecting which media mappings to enable or intensify. The coupling between media and action, and the lack of a physical device required for interaction, such as a mouse or a Wii remote, allow for an interactive rehabilitation system that centers attention on recovery of action, with little to no focus on the technology being used. Disruption in the continuous media composition, such as an indication of trajectory error, results from the participant's deviations in his physical reaching movement. This disruption leads to a decoupling of body, activity, and action for the discovery of the error.

4.2.4 Mixed reality: feedback should be designed for application within a spectrum of digital-physical environments to promote various levels of digital immersion. Environments that can change along a digital-physical continuum help control the level of dissociation from the physical experience (recontextualization) at each point of the training, while connecting learning in the virtual domain to physical action. Experiences such as training sequences must range from

primarily digital (the participant controls media-based feedback with his actions) to mixed (the participant interacts with physical objects while assisted by media-based feedback) to purely physical (the participant interacts with a physical object with no augmented feedback). Visual feedback designed for various levels of digital immersion should also change based on the location of the display. For example, detailed concurrent feedback provided on a screen (e.g. image particles coming together) will dissociate the patient from the task while simplified feedback provided in the action space (e.g. changes in color of an ambient light on the base of the object in HAMRR) should provide useful information that is easy to understand and fairly coarse in detail so as not to distract the participant. Visual summaries should not be provided in the path of the where the reaching action is located in order to avoid unwanted prescriptive effects of tracing.

4.2.5 Adaptation: feedback should be able to support participants of various ability, types of training, timescales of training, and training environments. To be relevant in a variety of contexts, feedback for INR must be able to react to changes stemming from the user or his environment (e.g. the individual's initial level of expertise, presence of external distracters). An experiential media system providing interactive feedback appropriate for stroke survivors of various levels of impairment must be capable of adjusting to different difficulty levels, types of impairment, and types of learning. Furthermore, because the recovery process is dynamic for each participant, the feedback must be adaptable in order to continuously engage, challenge and offer useful performance information to the stroke survivor.

The amount of movement error required to produce observable feedback error must be adaptable to the participant's ability and progress. A hull refers to the adjustable amount of error in a participant's movement that the system will tolerate before giving feedback that shows error (Figure 6). For example, in the clinical AMRR system adjustable, three-dimensional hulls control the feedback sensitivity for trajectory, joint function, and compensation. The feedback must be designed such that the minimum and maximum amount of error anticipated from movement analysis can be communicated, while effectively scaling in between.

The dosage of feedback should be able to change. Any number of feedback components must be easily added or subtracted without influencing the effectiveness of other components. Fading allows the partitioning of training into sections that each addresses few movement components so as not to overwhelm the participant. The same media environment should be able to be applied across multiple types of tasks (e.g., reaching to push a button, or reaching to grasp) in order to support generalized learning.

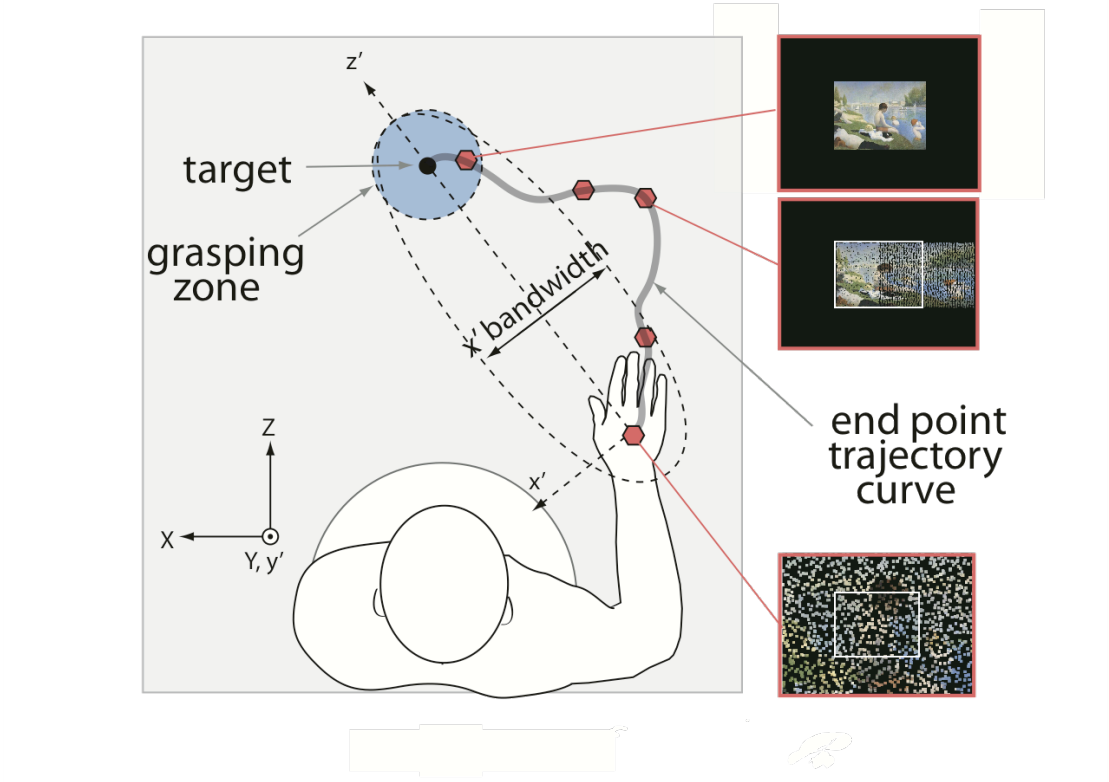


Figure 6. Adjustable hull space controls feedback sensitivity

4.2.6 Coaching: media should be designed to complement the gradual reduction in presence of a physical therapist. Coaching refers to the guidance or assistance provided to a participant by a knowledge expert to facilitate the participant's overall experience, general

understanding and/or skill acquisition. As previously mentioned in the introduction coaching is a key factor in INR media design: the role of a coach within the context of an experiential media system is to help train the participant to best utilize his/her interaction with the system. As a knowledge expert in the application domain, the coach can help curate these experiences (e.g. help the participant prioritize on which experiences to focus) before the participant has yet had the chance to develop internal models of how to best use the system to better perform the task at hand. In the context of motor rehabilitation for stroke, the coach is the physical or occupational therapist. Like the use of media-based feedback, the amount and nature of the coaching by the therapist can change over time and context. *Inquiry* based coaching involves the therapist asking the patient questions to promote critical thinking (e.g. “What do you think causes the visual feedback to look like that?”), while *prescriptive* based coaching can be verbal (e.g. “Rotate your wrist less in the beginning of your reach”) or physical (e.g. the therapist actively assists the patient to extend his elbow when reaching towards a target). Prescriptive coaching may be necessary initially in specific instances to avoid frustration. However type of supervision (e.g. decreasing prescriptive coaching and increasing inquiry based coaching) and amount of supervision (e.g. from the presence of the therapist at every session to visiting only every third session) need to fade as therapy progresses to encourage the patient to develop self-assessment strategies. Within the context of an experiential media system, coaching slowly fades over time to promote a peak in utilization of the media, before both are reduced to encourage the participant to draw from internal knowledge, which is depicted in the problem space shown in Figure 2 and displayed again in isolation in Figure 7. Supervised, semi-supervised and unsupervised training reflect the extent to which a coach is observing and assisting the stroke survivor while he engages with an experiential media system. The potential amount of coaching associated with each of these training types decreases. Both coaching and the media design should complement each other in the context of the application: for example, when feedback is heavily detailed and given in real-time during supervised training, we rely on the therapist to summarize this information across multiple trials (reaches), whereas in unsupervised training the media must be

able to communicate both detailed aspects of a single reach and summary across multiple reaches. Finally, the coach provides a human presence that cannot be removed or replicated by technology for rehabilitation training. Understanding the cognitive and emotional state of the participant is critical to the clinician's success in effectively curating the participant's experience with the system. A knowledgeable human presence is also often needed in order to establish the participant's trust in the system before semi- or unsupervised training can occur.

4.2.7 Network of applications. A network of systems is necessary to sufficiently address a broad experience space related to stroke rehabilitation, as outlined in Figure 2. Even an adaptive system cannot sufficiently address every phase of rehabilitation (ranging from clinical to home-based training, to monitoring activities of daily living) nor would such a system be feasible to provide low-cost solutions to long-term rehabilitation. Multiple applications along a continuum of experiential media systems should be optimized for specific phases of stroke rehabilitation. Each system within this network should support an aggregate rehabilitation experience that supports various stages of recovery. For example use of a home-based system should reinforce gains made in clinical rehabilitation but also introduce the patient to methods for self-evaluation. Adherence to the listed media design principles for INR can create a cohesive experience across multiple systems that target the patient's needs.

The following chapter proposes a compositional framework for applying these interdisciplinary concepts across a network of learning experiences for upper extremity stroke rehabilitation.

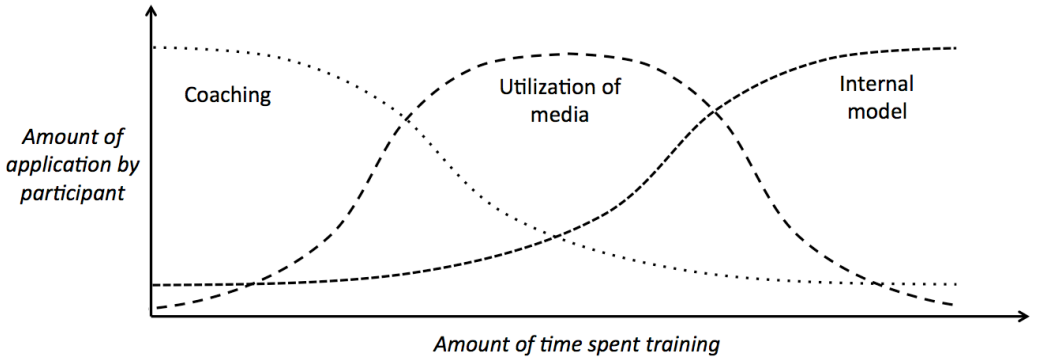


Figure 7. Utilization of coaching, media and internal models over time. Initially the participant will rely heavily on direction from the coach as s/he becomes more familiar with the media representation of his performance. As s/he begins to utilize the media, coaching is gradually reduced. Once the participant begins to internalize models for both evaluating and planning his future movement performance, utilization of the media should also be reduced as well.

CHAPTER 5

COMPOSITIONAL FRAMEWORK

5.1 Overview of framework

A compositional framework that provides an overall approach to using the interdisciplinary concepts is proposed to help media designers (1) tailor feedback to a particular phase of interactive learning while still support an experience that both (2) fits within the overall training continuum and (3) allows for movement in any direction along this continuum. While the order of learning phases can vary by participant, the desired aggregate effect of using a network of experiential media systems is for the participant to gradually achieve a complex learning goal while reducing dependence on augmented feedback. The following sections summarize the compositional framework for designing media for INR at a high level, followed by more detailed discussion of the framework's expression across multiple systems for INR.

5.1.1 Composing media for supervised training. Interactive training in supervised contexts (such as the clinical AMRR system) is designed to facilitate a shift from the participant's use of coaching to use of the system's augmented feedback, while also gradually begin the formation of an internal model. Training should focus on component-level learning (e.g. extending the arm forward) and a range of simple (e.g. reach to grasp a cone/touch button) to more challenging (e.g. reach to grasp an elevated cone) repetitive tasks. All activity trained can be reduced to a core single-phase action (in the case of the AMRR system, a reaching task). The media design should therefore be based upon a representation of this action, which both identifies a manageable number of kinematic features describing invariant aspects of movement and describes the overall relationship among these components. See Figure 8 for an example action representation for reach and grasp.

Each feedback component provided during supervised training encodes the magnitude and direction for improvement of an individual movement feature within the action representation. Media is provided concurrent to movement and terminally to facilitate immediate correction of error (when possible). The type of abstract media conducive for this application draws attention to

simple elemental aspects of the media's form (e.g. visual direction, shape; audio note density, volume) that also function in an integrated manner (e.g. particle movement forms a picture while communicating hand spatial error and rhythmic density communicates hand speed with a harmonic progression resolving the same time as the image is formed) reflective of the action representation (e.g. the most dominant aspects of media reflect the movement components that are most influential on task completion). While the mapping between a feedback element and aspect of movement is simple and easily deduced, feedback still needs to range in function, facilitating both explicit and implicit information processing depending on the movement component (e.g. feedback on timing requires more implicit processes).

The coach (e.g. the supervising physical therapist) adapts the system by changing tasks, enabling or disabling different types of feedback, as well as by adjusting their respective sensitivities, in an effort to maintain engagement, avoid frustration, and sustain challenge. S/he complements elemental training with the media by providing the participant with high-level feedback on performance over various timescales (e.g. summarizes performance over the course of a session and/or week). The feedback also provides a medium for inquiry-based communication between the coach and participant, by allowing the coach to ask questions based on the resultant feedback (e.g. what did you see and why).

5.1.2 Composing media for unsupervised training. Interactive training in unsupervised contexts (such as the home) should increase the participant's confidence in performing more complex tasks independently. An interactive feedback environment suitable for home-based training should incentivize long-term usage of the system; effectively communicate performance of activities that range in complexity; and increase self-assessment by fading dependence on explicit, concurrent feedback. Thus the semantics of the feedback provided during unsupervised training should connect the participant with a larger narrative of his/her recovery, one that is more manageable than the detailed training in the clinic and also draws from the varied types of feedback provided by a coach. Also given the reduced presence of a therapist, an interface for providing instructional content on tasks and feedback is necessary during training sessions, as

well as a means for the therapist to provide intermittent high-level feedback to support the formation of the long-term narrative of training.

While the primary consideration for composing media for supervised training is the overall form of an individual *core action*, in unsupervised training there are multiple *activity levels* stemming from a core action (e.g. reaching task) to gradually advance the participant towards more complex tasks. In this case, the form of the feedback needs to support awareness of performance within and across these multiple activity levels. Thus rather than providing feedback on all aspects of activity (which is also more difficult to capture robustly in unsupervised training), the feedback focuses on fewer key aspects of movement relevant across each activity level.

Without the coach curating the experience in real-time (e.g. removing or adding feedback) and providing high-level observations every session (e.g. connecting low-level training to overall functional improvement), the feedback must also be designed to facilitate the participant's formation of internal models to a greater extent than feedback designed for supervised training. Compared to assistive feedback that draws attention to changes in strictly the *elemental formal* aspects of the media, each of which are tied to individual movement components, more complex task training requires a shift in feedback semantics that parallels the activity structure. For example, complex tasks are not necessarily reducible to individual kinematic features that would benefit from stylization, as often multiphase movements are more variant even among non-impaired movers. To help support a shift in semantics, feedback can encourage a participant's attendance to *the combined effect of these elements* within a scene or music composition. Thus the participant is decoding summaries in an individualized way that, when paired with low-level training on simpler related tasks, could facilitate the unique formation of internal models appropriate for the participant. To help the participant associate low-level training results, in which specific feedback is provided on how to correct movement, to higher levels of training, in which feedback is less specific and more suggestive, a reductive hierarchy is used. A reductive hierarchy establishes a language of mappings that connect different levels of training, such as color being provided for magnitude of spatial error across different levels of

training. Thus while feedback becomes more abstract in higher levels of training (e.g. by providing less specific information on how to correct spatial error), holding some aspects constant (e.g. color provided to indicate magnitude of error) can help the participant associate higher level results with strategies gained from lower level training.

Visual content that has meaning outside of training (e.g. a boat, water environment, traveling) is used to provide a narrative structure that parallels the hierarchical levels of training to help participants map overall progress. As training increases its complexity, the feedback becomes more narrative-driven (requiring the participant's decoding of media as previously mentioned). If activity complexity and semantic complexity are both increasing, the time delivery of feedback should be used to balance the experience by decreasing the amount of time before feedback is provided for complex tasks. This process is discussed later as two-dimensional fading given that both performance information and time delivery of feedback change based on activity complexity.

Finally while coaching is reduced, the physical therapist is still needed to both introduce the participant to the feedback-training space as well as assist reflection on timescales longer than those covered by training. Before unsupervised training begins the participant trains with the presence of the therapist for a brief introductory period (e.g. for the home-based AMRR system, the first 20% of training sessions) to provide a means for answering questions on feedback or tasks. Intermittent feedback by the therapist should also be provided over the course of unsupervised training to help the participant form an overview of his progress with respect to specific movement challenges. The form of this feedback should combine the therapist's commentary with explicit examples of performance that are easily understood (e.g. in the home-based AMRR system videos are composited into 'stories' communicating progress). Direct representation media such as video of the participant performing tasks balances the provision of feedback over longer timescales (e.g. from previous weeks) while still providing a means for therapists to discuss higher-level concepts of movement and training.

5.1.3 Composing media for long-term reflection. While currently a system for long-term reflection is missing from the AMRR network of systems, one can extrapolate from the space shown in Figure 5 that a range of complex tasks to activities of daily living should be performed with a reduced presence of media feedback and coaching. The weekly meetings with the therapist used in conjunction with unsupervised training provide a starting point for facilitating reflection over longer timescales, and may also benefit participants in this later stage of training. The presence of real-time feedback should be reduced to intermittent indicators (e.g. audio indicators) while visual feedback should be used for the presentation of long-term activity summaries. Finally, the stroke-survivor should be part-creator in the design of these interactions to further support long-term interest and compliance. More discussion of extending the framework for long-term reflection is provided in Chapter 8: Future Directions.

The following sections revisit the concepts introduced above in more detail by describing the compositional framework as expressed within the clinical AMRR system, the home-based AMRR system, and an iPad app for assisted reflection.

5.2 Feedback Environment for the Clinical AMRR System

The clinical AMRR system provides a foundational experience in mediated training. The participant is provided with detailed information about numerous aspects of his performance in an environment that is closely monitored and adjusted by the therapist (coach). The range of activities performed is relatively simpler than those trained in the home-based AMRR system and include reaching forward, reaching to touch a button, and reaching to grasp a cone. The task type, amount of feedback and sensitivity of feedback are adjusted by the therapist as needed in an effort to maintain engagement, avoid frustration, and sustain challenge. The AMRR feedback focuses primarily on communicating individual aspects of real-time performance, and over time and exposure to the system, their inter-relationship. All feedback is abstract and primarily assistive in function: magnitude and direction of error are emphasized to facilitate the participant's self-evaluation and correction.

The AMRR system's design is based on a reduced representation of the reach and grasp action based on prior work identifying key features in upper extremity movement and motor learning (Morasso, 1981; Abend, Bizzi, & Morasso, 1981; Schmidt, 1991; Richards & Pohl, 1999; Krakauer, Mazzoni, Ghazizadeh, Ravindran, & Shadmehr, 2006; Krakauer, 2006). The action representation is populated by key kinematic attributes that quantify the stroke survivor's performance with respect to each category of movement. Some kinematic attributes calculated during the reach and grasp action are used in real-time to generate media-based feedback, while others are used for post-movement analysis of the participant's action. Features expressed to the participant through feedback are key invariants of goal-directed reaching movement that and can be applied across different types of reaching activity. Figure 8 presents a simplified action representation of a reach and grasp action as a nested network of key kinematic parameters. These kinematic features are organized into seven sub-categories of movement attributes, based upon operational similarities within the reach and grasp movement. The seven sub-categories are classified as either activity measures, extracted from the participant's end-point (hand) spatial and temporal performance, or body function measurements, describing the function of relevant body structures other than those extracted from the hand during a reach and grasp action. Overlap between categories indicates the potential amount of correlation among kinematic parameters. Sub-categories located close to the center of the representation have greater influence on goal completion.

The structure of the action representation guides the overall feedback design. While each feedback component is designed to address challenges associated with a specific movement attribute, all components are designed to connect as one real-time audiovisual narrative that communicates overall performance of the action. Following the structure of the action representation, feedback is provided on performance of *activity level parameters and categories* and *body function level parameters and categories*. The *integration of individual feedback components through form coherence* also reveals the interrelationships of individual parameters and relative contributions to achieving the action goal.

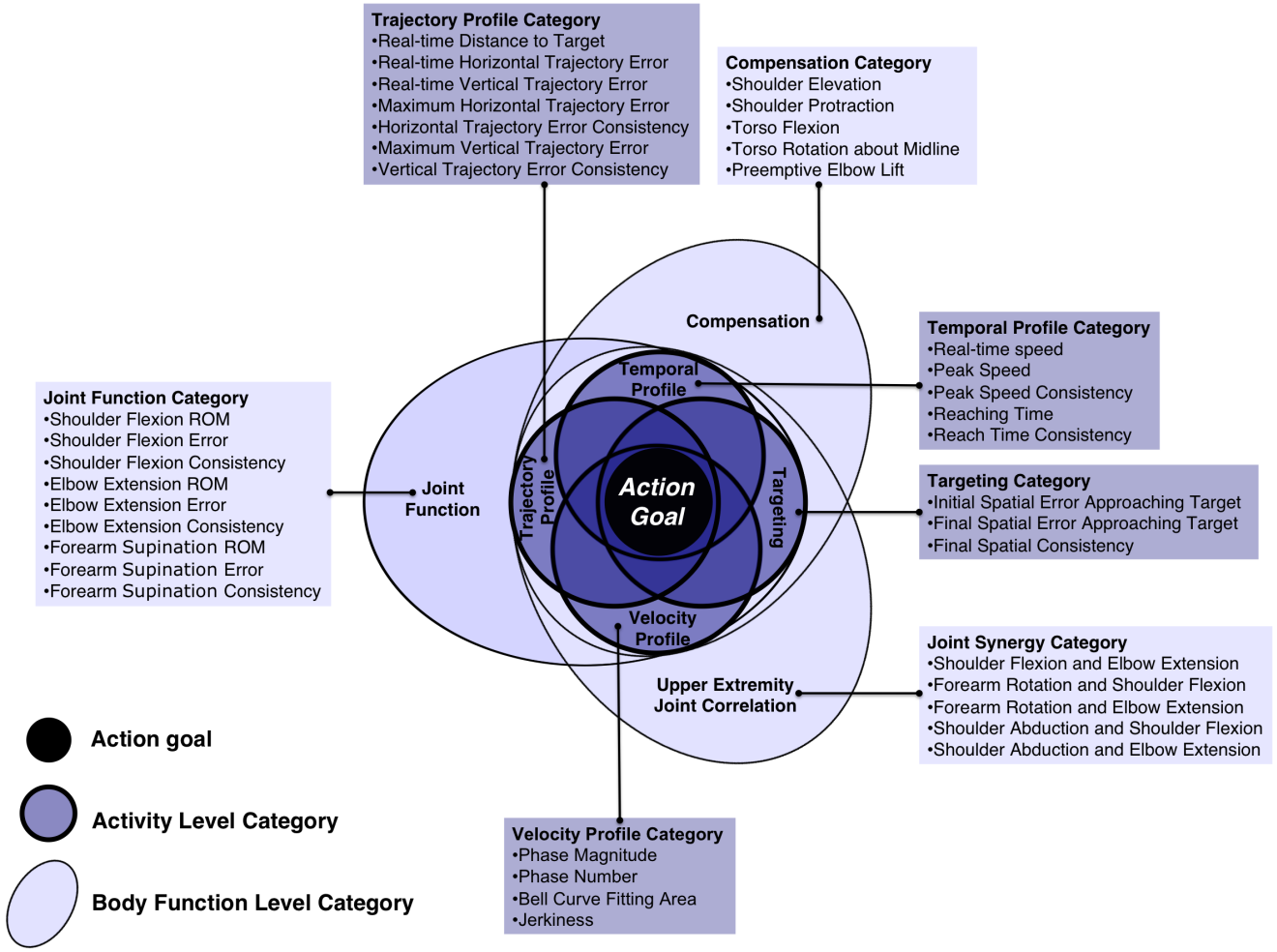


Figure 8. Action representation of a reach and grasp. Key features contributing to reach and grasp movement are identified and organized based on similarity. Adapted from *Chen, Duff, & Lehrer, 2011*, Copyright © 2011 Thomas Land Publishers, Inc. www.thomasland.com

5.2.1 Feedback on activity level parameters and categories. Feedback on activity level parameters must assist with the movement challenges that most significantly impede the efficient performance and completion of a reaching task. Correspondingly, feedback components reflecting activity level parameters are the most detailed and prominent audiovisual elements within the AMRR feedback. Below are examples of how specific feedback components are designed to target movement challenges. All feedback in the real-time environment was designed by AMRR members Loren Olson, Todd Ingalls, and Isaac Wallis. Summary feedback was designed by the author.

Activity level category: trajectory profile. Movement Challenge: Many stroke survivors have difficulty planning and executing a linear trajectory while efficiently completing a reaching movement to a target, especially without visually monitoring movement of the affected hand (Scheidt & Stoeckmann, 2007).

Feedback Components: The animated formation of an image from particles, depicted with an emphasis on visual linear perspective, describes the end-point's progress to the target while encouraging a linear trajectory throughout the movement. As the participant reaches, his end-point's decreasing distance to the target "pushes" the particles back to ultimately re-form the image when the target is reached. As the expanded particles come together, the shrinking size of the image communicates distance relative to the target. The shape of the overall image is maintained by the end-point's trajectory shape: excessive end-point movements in either the horizontal or vertical directions cause particles to sway in the direction of deviation, which distorts the image by stretching it. Magnitude of deviation is communicated by how far the particles are stretched, and direction of deviation is communicated by which side of the image is affected (e.g., top, bottom, right, left, or combination thereof). To reduce the distortion of the image, the participant must adjust his end-point in the direction opposite of the image stretch. Formation of the image, as the most prominent and explicit stream among the feedback mappings, not only provides a continuous frame of reference for trajectory distance and shape but also communicates progress towards achieving the goal of the completed image. Furthermore, by

using visual information on the screen to complete the action, and thus not simultaneously focusing visually on his hand, the participant reduces reliance on visual monitoring of his end-point. See Video 7 listed in Appendix E for an example of the image stretching to indicate trajectory error.

Design Concepts Applied: *Visual* feedback is best suited for communicating three-dimensional spatial information. Because information is provided in terms of direction and magnitude of error the feedback is *assistive* in function: particle movement is directly linked to end-point movement in order to *explicitly* describe the end-point's spatial deviation from or progress towards achieving an efficient trajectory to the target. The feedback is delivered *concurrent* to action and *continuously* to allow the participant to observe movement of his end-point by monitoring formation of the image, and when needed, apply this information for *online control* of his movement to adjust for vertical or horizontal deviations.

Movement Challenge: Sometimes stroke survivors are unable to utilize online information during task execution to develop a movement strategy, and require feedforward mechanisms to assist with planning proceeding movements.

Feedback Components: A static visual summary communicates overall maximum trajectory deviation after each reach is completed to facilitate memory of real-time trajectory error. The summary presents a series of red bars. Their location on the screen (e.g., high, low, left, right, or combinations thereof) represents where error occurred in terms of vertical and horizontal coordinates (along the x, y axes respectively). Visual perspective is used to communicate the distance at which error occurred (along the z axis) through spatial depth. A deviation occurring in the beginning of the movement appears closer to the viewer in perspective space, while deviations that occur later appear further away. The number of red bars conveys the magnitude of trajectory error. See Video 7 listed in Appendix E for an example of the trajectory summary displayed after the reach. Trajectory deviation is summarized from rest position until the hand's entrance into the target zone (an adjustable area surrounding the target that determines task

completion), excluding the fine adjustment phase, as it likely does not contribute to feedforward planning of the reaching trajectory (Scheidt & Ghez, 2007).

Design Concepts Applied: *Visual* perspective is used to communicate the reaching distance as spatial depth. The summary, like the image formation, is *assistive* in function and provides an abbreviated history of the continuous particle movement by *explicitly* illustrating the magnitude (number of bars) and direction (location on screen) of trajectory errors. Presenting an *offline terminal* visual summary allows the participant to make a global comparison of timing, location and magnitude of his trajectory deviations within the context of the entire reach. This display may also facilitate the *implicit processing* of the connection to memory of performance on other aspects of movement (e.g., the participant remembers hearing a shoulder compensation sound indicator in the beginning of the reach, and also sees red error bars on the top of the screen within the summary). Connecting real-time movement to *offline* contemplation can inform *feedforward* planning of successive movements.

Activity level category: temporal profile. Movement Challenge: From the volitional initiation of movement until the completion of the reaching task, stroke survivors often have difficulty planning and controlling acceleration, trajectory speed, and deceleration of their movement across a defined space. This challenge makes relearning efficient movement plans difficult.

Feedback Components: The musical phrase generated by the participant's movement is designed to help monitor and plan the timing of movement, as well as encourage completion of the action goal. The end-point's distance to the target controls the sequence of chords of the musical phrase. The reach is divided into four sections with different musical chords played for each. The sequence of chords follows a traditional musical pattern (with some randomized variation to avoid repetitiveness) that underlies many popular songs and is thus more likely to be familiar to the participant. The participant may intuitively associate each part of the reach with a corresponding part of a musical sequence (early, middle, late part of the movement/sequence) and be motivated to finish the reaching task to complete a familiar audio composition. If the end-

point deviates from an efficient trajectory towards the target, the musical chords detune for the duration of deviation to place in time the occurrence of the deviation (whereas the spatial information of the deviation is communicated by the image stretching). End-point speed is mapped to the rhythm of the musical phrase. The participant's movement speed results in a "rhythmic shape" (change of rhythm over time) that most strongly encodes the end-point's acceleration during reach initiation, the deceleration when approaching the target, and the overall range of speed. Aggregate memory of the resultant rhythmic shape (i.e., which rhythmic pattern is associated with the best reaching results) can assist the participant to develop and internalize a representation of end-point speed that helps plan his performance. See Video 7 listed in Appendix E, which shows an efficient reach, followed by a reach with detuning as a result of trajectory deviation, and a reach with slow speed and thus lack of rhythmic shape.

Design Concepts Applied: Audio feedback is best suited for communicating temporal movement aspects. Musical feedback is controlled by the end-point's speed and distance, and communicates the end-point's *concurrent* progress towards the target in a *continuous* manner. In accompaniment to explicit visual monitoring of the image formation, the audio communicates changes within the end-point's temporal activity and encourages *implicit* information processing of the rhythm as a singular remembered form (i.e., memory of the rhythmic shape). Memory of the musical phrase supports *feedforward* mechanisms for planning future movements and facilitates comparison across multiple reaches (e.g., speed consistency of reaches within a set). The detuning of the harmonic progression adds a timestamp to the visual stretching of the image to assist *feed-forward* planning.

Activity level category: velocity profile. Movement Challenge: Many stroke survivors do not exhibit a bell-shaped velocity profile characteristic of unimpaired reaching movement, as a result of difficulties with timing and executing an efficient trajectory.

Feedback Components: Simultaneous feedback streams describing the participant's end-point behavior can help the participant in relating the temporal and spatial aspects of his reach. The acceleration/deceleration pattern communicated by the rhythmic shape of music assists the

participant in understanding speed modulation. The shrinking size of the image and harmonic progression communicate his distance and overall timing to reach the target. Coupling these simultaneous mappings allows for changes in speed to be connected to distance and facilitate the development of an integrated space-time plan. Figure 9a-9e illustrates how (e) velocity profile is communicated as an extracted, integrated descriptor of the (b) image progression, (c) harmonic progression, and (d) rhythmic progression, relating the end-point's distance, direction, and speed towards the target.

Design Concepts Applied: As a complex aspect of movement, the velocity profile cannot be effectively expressed as a singular feedback component, for a singular mapping would not allow the participant to determine which aspect of movement (speed, direction, and/or distance) requires adjustment that generalizes to multiple types of reaching tasks. Therefore, feedback on the velocity profile is observed through extracted information processing, in which the participant integrates information from both visual and audio streams reflecting directed distance and speed. Form integration of relevant audio and visual mappings into a unified velocity profile is encouraged by feedback feature selection: all involved components are *concurrent* and *continuous* mappings of end-point movement. *Extracted* information processing of the velocity profile may facilitate *feedforward* planning of acceleration and deceleration patterns along a given reaching distance to a target.

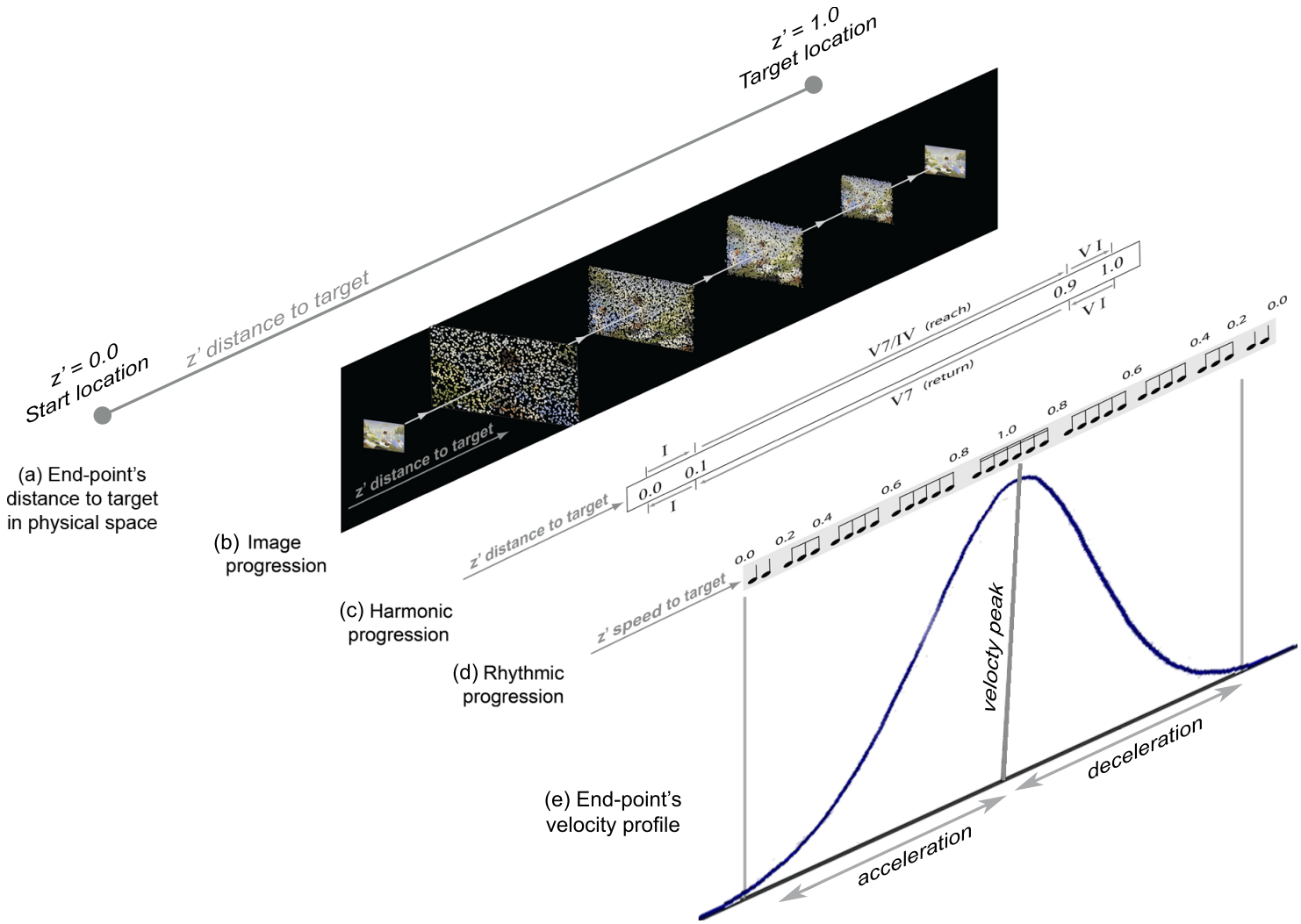


Figure 9. Three parallel feedback streams communicate hand's spatial temporal behavior.

5.2.2 Feedback on body function level parameters and categories. Body function level feedback must assist with challenges impeding the relearning of premorbid movement patterns of specific body structures relevant to reach and grasp performance. Feedback on body function parameters is coarse and discrete, thereby temporarily directing attention to specific body structures without distracting from completing the action goal. When a clinician must focus training on regaining functional independence primarily through teaching compensatory mechanisms, training for improved body function may not be appropriate (Krakauer, 2006; Levin, Kleim, & Wolf, 2009). Accordingly, in the clinical AMRR system, body function mappings can be independently toggled on or off at the discretion of the clinician.

Body function level category: shoulder and torso compensation. Movement Challenge: To compensate for lack of extension during a reach, many stroke survivors use excessive shoulder movement (elevation and/or protraction) and excessive torso movement (flexion and/or rotation).

Feedback Components: Compensatory movements are signaled by distinctive sounds that can interrupt the musical phrase (foreground) generated by end-point movement. Excessive shoulder compensation during a reach causes a cymbal sound while excessive torso compensation causes a crackling sound. These compensation indicators may be enabled individually or simultaneously, and are activated when the participant moves beyond an acceptable range of movement. Because these sounds do not combine well with the musical foreground in terms of harmony, timbre and rhythm, they draw the participant's attention to body structures exhibiting inefficient movement strategies. See Video 8 listed in Appendix E for examples.

Design Concepts Applied: Unique audio feedback indicators provide *explicit* indication of either shoulder or torso compensation *concurrent* to action for *online control* and correction of error. These *auditory* cues allow for *intermittent* monitoring of specific body functions amidst continuous end-point monitoring. As audio indicators, *implicit* information processing of these sounds caused by compensatory movements may be integrated into memory of the overall musical phrase and overall performance to assist with feedforward planning.

Body function level categories: joint function & upper extremity joint correlation. A description of feedback used for joint function (wrist rotation and elbow extension), and for communicating the relationship among multiple joint movements, can be found in Appendix C.

5.2.3 Integrating individual feedback components through form coherence and aggregation. The connection between feedback components and corresponding movement components must be intuitive and easily perceived. Simplifying training by only offering feedback on one element at a time is not an optimal solution. Some stroke survivors cannot connect individually learned aspects of performance into a complete, generalizable, sustainable strategy (Krakauer, 2006). The higher-level organization of the feedback must facilitate integration of multiple media components into one coherent media narrative. A summary of feedback mappings and concepts applied is provided in Table 13. As shown in the previous section, the clinical AMRR system facilitates integration of multiple media streams through (a) appropriate selection of feature choices for feedback mappings (e.g., audio for time, visuals for space), (b) compositional strategies that integrate closely related streams (e.g., time and space elements of velocity profile), and (c) parallel action and feedback narratives (e.g., successful completion of the physical action goal completes the interactive media narrative). These three strategies establish formal coherence between action and media.

5.2.4 Adaptation, Coaching, and Multileveled Feedback. The clinical AMRR system is designed for a supervised context, in which the therapist can adapt the system, provide coaching and complement the real time feedback with higher-level assessment. The primary components of the clinical AMRR system that may be adapted include target type and location, selection and sensitivity of media components, and training environment. Training is conducted in sets of ten reaches. Task type and feedback may be adjusted after each set. The clinician may guide the training focus for each set by selecting which feedback to use. The clinician's choices also control the level of feedback complexity provided to the participant. Furthermore the sensitivity of each enabled feedback component may be independently adjusted, which allows the clinician to set the appropriate level of difficulty for each movement attribute.

Different training environments may be used within the clinical AMRR system by controlling the amount of media-based feedback (virtual) and task (physical) components applied. The system provides for gradual transitions between virtual and physical training by using three types of training environments: physical (provides no media-based feedback while reaching to a physical target), hybrid (provides combinations of media-based feedback while reaching to a physical target) and virtual (requires interaction with only media-based feedback and no physical target). Multiple available variants (gradations) of these environments enable the clinician to shift training on a continuum towards a more virtual (for recontextualization) or more physical (for reduced or no feedback guidance) environment depending upon the participant's needs and stage of training. For each set of ten reaches, the treatment clinician typically chooses one or two limitations from the limitation profile on which to focus. Assisted by the media specialist, the clinician may then select the appropriate task components (target type and location), media-based feedback components (which feedback components to enable and respective sensitivities) and type of training environment (virtual, hybrid, physical) to utilize for training. Sequential modifications of these training components and movement aspects form the adaptive training. After each set, the system's quantitative evaluation, coupled with the clinician's direct observation, inform the adaptation decisions for the proceeding set.

Finally the physical therapist provides the participant with high-level feedback on his performance across sets or weeks. For example in the clinical AMRR study described in Chapter 3, the therapist was able to give a birds eye view of training by keeping track of movement challenges trained over time, explaining which aspects seemed to be improving based on the feedback the participant experienced and the evaluation numbers the therapist saw. The media also provided an opportunity for the therapist to ask the participant what s/he thought about his/her performance before the therapist provided feedback.

Table 13

Summary of feedback mappings and applied concepts for the Clinical AMRR system

Activity Level Features	Corresponding Feedback Components	Sensory modality	Time delivery	Function	Usage goal
Trajectory	Magnitude and direction of image particle movement	visual	concurrent continuous	assistive explicit	online control
Forward movement	Harmonic progression	audio	concurrent continuous	assistive implicit	feedforward
Trajectory	Summary of error	visual	offline terminal	assistive explicit	feedforward
Speed	Rhythm of music	audio	concurrent continuous	assistive implicit	feedforward
Velocity Profile	Image formation integrated with musical progression	audio-visual	concurrent continuous	reflective extracted	feedforward
Body Function Level Features					
Forearm rotation	Image rotation	visual	concurrent continuous	assistive explicit	online control
Elbow extension	Volume and richness of orchestral sounds	audio	concurrent continuous	assistive implicit	online control/ feedforward
Torso compensation	Abrupt disruptive sound	audio	concurrent intermittent	assistive explicit	online control
Joint correlation	Temporal relationship among feedback mappings	audio-visual	concurrent continuous	reflective extracted	feedforward

5.3 Feedback Environment for the Home-based AMRR System

Clinical AMRR focused on training motor elements (e.g. trajectory, speed, elbow extension, wrist rotation) within a single reach, which required high-resolution sensing to support detailed real-time feedback for both activity and body level performance. The physical therapist also supervised training and adjusted tasks and feedback based on the needs of the participant. The goal of the home-based AMRR (HAMRR) system was to provide a lower-cost means for unsupervised training that also focused on higher-level aspects of movement quality and overall functionality, in more complex tasks reflective of everyday activity. While the movement

challenges commonly faced by stroke survivors remain the same as those addressed by the clinical AMRR system, a reduced sensing infrastructure appropriate for the home results in fewer movement features captured at a lower resolution. The feedback addresses fewer key features at various levels of resolution (e.g. the concept of trajectory path on a per to multiple reach basis) rather than the breadth of various features assessed in the clinical system. Unsupervised training also requires participants with a higher degree of functionality in order to perform more complex tasks with minimal assistance. In the network of AMRR systems, use of the home system would theoretically follow one month of training with the clinical AMRR system, familiarizing participants with the use of media to assess performance and helping to train lower level aspects of movement.

Interaction with the home system is separated into 3 levels, where a level describes the manner in which both the task and feedback are structured. Level 1 offers concurrent and terminal feedback per single repetitive action, which involves reaching to and manipulating a specified target object. The most detailed feedback is provided to the participant to increase his awareness of the specific nature of his movement performance (e.g. magnitude and direction of spatial error) within an individual action. In Level 2, summary feedback is provided following a group of repetitive actions that involve reaching to and manipulating a specified target object. Coarse feedback is provided to the participant to increase his awareness of the overall quality of movement (e.g. overall spatial or temporal quality) across a group of reaches. Level 3 provides summary feedback on a complex task that may take one of two forms: A *sequence* task requires the participant to perform a pair of actions that involve reaching to and manipulating one specified target, then directly reaching to and manipulating another. A *transport* task requires the participant to reach to and transport a portable object from its initial location to a second specified location, return to rest and then, reach to and transport the object back to its original position. Coarse feedback is provided to the participant to increase his awareness of the overall efficiency of his movement (e.g. integrates spatial, temporal, and target manipulation) for the sequence or transport task. The three levels of training focus on evaluating and providing feedback on reach

path, reach speed, hand manipulation of target, compensation and transport. More information on quantitative evaluation of each movement per level is provided in Appendix D.

The feedback-user interaction within the home system required a reduction in concurrent detailed feedback and an increase in summary information provided offline, due to the lack of detailed capture and supervision, as well as the desired increase of self-assessment. Continuous online feedback could not be administered on the screen mainly because it would likely detract from focus on the action space, while in the hospital the level of dissociation could be finely controlled for (e.g. if the participant needed to visually focus on the physical space visual feedback was reduced or turned off). In the home system the visuals were used to structure the interaction in two phases: (1) lights embedded in the reaching targets directed attention to the physical target and provided coarse feedback on magnitude of error across three color categories, while (2) visuals presented on the screen were reserved for detailed offline summaries of spatial performance. Each of the three levels of feedback progressively reduced the explicit display of error provided while increasing the use of inferential narrative to communicate performance. The explicit goals within the visual media were the formation of a straight rock path, the maintenance of the structural integrity of a boat, and the creation of calm scenes for traveling. Any perturbation to these visual features communicates a deviation from efficient activity performance, however to challenge the patient and increase independent evaluation, the visual summaries required more contemplation than real-time feedback embedded in the table. The continuity of visual mappings (e.g. color and/or shape) across different mediums (physical versus screen-based) and levels of activity (Level 1-Level 3) are also designed to form a distributed narrative of performance that can be trained in any order or dosage.

5.3.1 Level 1. During Level 1 interaction, the participant receives concurrent and terminal feedback on an individual reach. Each feedback component listed in Table 14 is modular and may be used in any combination, aside from the requirement that task completion feedback always be enabled and that any terminal feedback on a performance component must also be

reflected in real-time (e.g. terminal rock summary only follows a reach with concurrent feedback on trajectory).

The real-time interaction refers to the stage during which the participant performs a task and receives concurrent feedback. LEDs embedded in the base of a target provide information based on color. A white light provides an initial go cue. Once the participant begins to reach the light remains white as long as the hand's location is within a zone of non-impaired variation. The light turns yellow to communicate instantaneous reaching performance is slightly inaccurate, or red to communicate it is severely inaccurate. At task completion, a green light success cue is provided towards the top of the target (top of the cone, outer circle of flat object, outer circle of button) to signal to the participant he has completed manipulation of the object and can return to rest. The real-time interaction therefore establishes a color vocabulary of white for efficient, yellow for slight error, red for severe error, and green for successful task completion. See Video 3 for an example of the color-based feedback provided during the real-time interaction.

Table 14
Feedback mappings for Level 1

Time delivery	*Movement feature*	*Feedback mapping*
Concurrent*	Hand trajectory accuracy	Colored lights in base of target
	Task completion	Green light success cue
	Hand speed	Rhythmic progression of music
	Torso compensation	Fog horn sound
	Lift success	Swish sound
Terminal	Hand trajectory accuracy	Rock path
	Lift success	Fog clearance

* Sound by Todd Ingalls, interactive objects by Margaret Duff

Real-time speed is communicated by the density of notes played in the accompanying musical feedback, in a similar manner as was used in the clinical system discussed in Section 5.2. When the participant reaches the target object the musical progression resolves. Excessive movement of the torso, referred to as torso compensation, is communicated using a foghorn sound. If the participant is directed to also perform a lift task following the grasp of a portable object, he receives a unique success cue that the object was raised to an acceptable height. An

example of the audio feedback provided on speed and torso compensation can be heard in the interactive set provided in Video 2.

Terminal feedback is provided on trajectory accuracy and lift performance. Trajectory accuracy is communicated using a rock path that changes shape and color based on spatial accuracy of the hand. Lift performance is communicated as the clearance of fog. The following sections describe in more detail how the terminal visual summary implemented by the author communicates performance and connects to the real-time interaction.

Communication of performance in the terminal feedback. To train spatial accuracy, the participant's performance of a reach generates a path of rocks leading to a boat, displayed on the screen following the reaching task's completion. The length of the reach is divided into 20 segments; within each segment, 4 vectors that describe the maximum deviation from the non-impaired zone are recorded. Each vector describes deviation in a unique direction: left, right, up and down. The participant is challenged to create a straight path of white rocks by reaching efficiently, or as close to remaining within the zone of non-impaired variation as is possible, such that these deviation vectors are minimal.

If the hand significantly deviates vertically or horizontally beyond the zone of non-impaired variation, the color, shape and/or location of the rocks are affected. Horizontal deviation from an efficient path results in yellow or red rocks that are spread to the left or right of the path depending upon the direction of deviation; the extent of the spread is proportional to the magnitude of the deviation vector. Deviation in the positive vertical direction results in yellow or red rocks that are elongated in height. In this case, the height of the rocks is proportional to the magnitude of the deviation. Deviation in the negative vertical direction results in rocks that appeared to have sunk underwater. Each deviation vector is also classified in terms of the severity of the error magnitude, which determines the rock's color (just as deviation in real-time controlled the target light's color). Rocks are yellow if the error magnitude is rated 1 for moderate, red if the error magnitude is rated 2 for severe. Otherwise negligible errors are rated as category

0 for efficient, and the rocks are white and smooth. Table 15 summarizes how each type of deviation vector affects the rocks' appearances.

When horizontal and vertical errors occur together, i.e. within the same reaching segment, the information is visually composited. The elongated vertical rocks resulting from positive vertical error or the sunken underwater rocks resulting from negative vertical error are spread in the magnitude and direction of the horizontal error. The rock color is determined by the maximum error between the two direction components; if at least one component was severe in error magnitude, then the rock is colored red. Otherwise if both horizontal and vertical error magnitudes are moderate, then the rock is colored yellow. A special case, described in more detail later, is negative vertical error without a horizontal component, in which rocks are colored black. Table 16 summarizes how information is composited when both horizontal and vertical errors occur together. Figure 10 illustrates 3 example reaching paths: an efficient path, a path with pure horizontal error, and a path with composite error. Video 10, listed in Appendix E, shows an example path with negative vertical error.

Table 15
Drawing rules per path segment for single component error

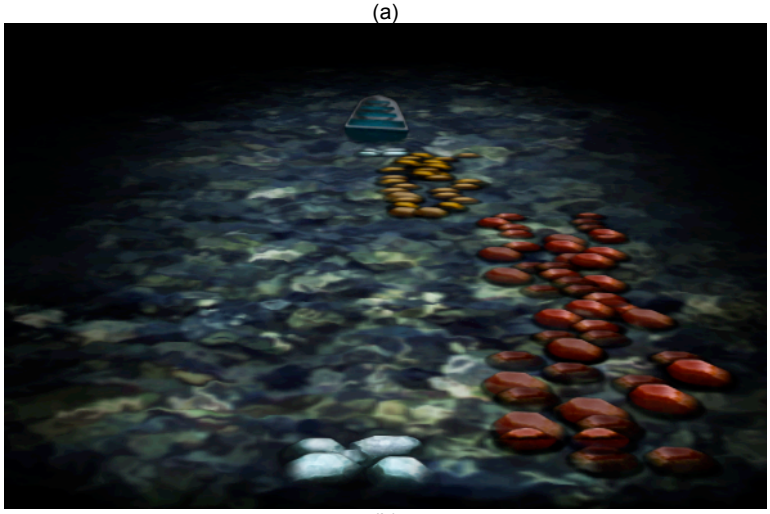
Deviation vector	*Alters rock location/shape*
Positive horizontal	Translates rock left by a distance proportional to vector magnitude
Negative horizontal	Translates rock right by a distance proportional to vector magnitude
Positive vertical	Elongates rock height by a size proportional to vector magnitude
Negative vertical	Adds underwater effect
Category magnitude	*Alters rock color*
0	White
1	Yellow
2	Red

Table 16
Summary of composite and single-component errors decision matrix - only cases for positive horizontal error and positive vertical error are presented, for simplified illustrative purposes.

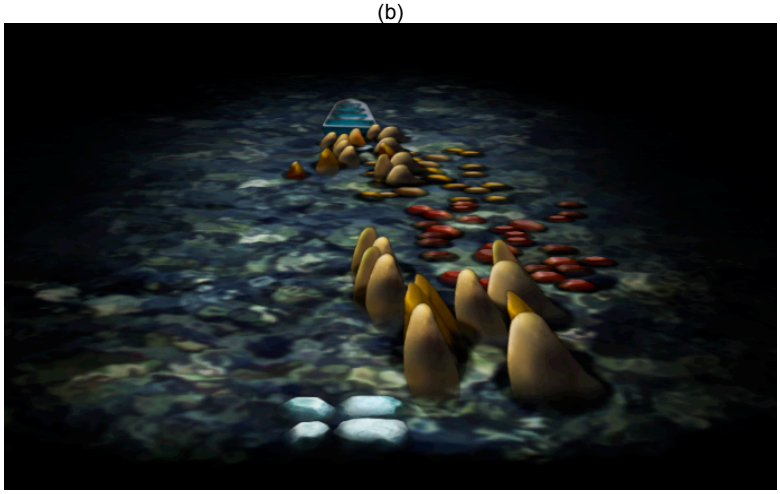
	No vertical error	*Category 1 positive vertical*	*Category 2 positive vertical*
No horizontal error	White rock	Yellow tall rock, no shift	Red tall rock, no shift
Category 1 positive horizontal	Round yellow rock shifted to the left	Yellow tall rock shifted to the left	Red taller rock shifted to the left
Category 2 positive horizontal	Round red rock shifted to the left	Red tall rock shifted to the left	Red taller rock shifted to the left



(a)



(b)



(c)

Figure 10. Examples of Level 1 terminal visual feedback on spatial accuracy. (a) efficient path, (b) path with horizontal deviation to the right, (c) path with horizontal and positive vertical deviation.

Mappings are designed such that participants can still decouple composited errors as needed (e.g. the participant can discern if the vertical component of a composite error was large or small in order to adjust his movement strategy). Sometimes horizontal and vertical errors that occurred within the same reach segment should not be coupled because they are unrelated. In this case errors are represented individually; often these cases reflect a backtracking of the hand in which a different directional error was made than previously, or movements that are highly erratic, shaking the hand in the lateral or vertical direction, as the participant reaches forward.

Level 1 also required feedback for a potential reaching task that concludes in a lift. After a reach to lift task was performed, a layer of fog appeared on top of the level 1 scene. If the lift met a height threshold, then the fog would immediately clear from view. If the lift did not reach the height threshold then the fog would remain on screen, partially obscuring the boat and path. Figure 11 shows an example scene if the lift was unsuccessful. A closer view of the fog clearing can be see in Video 11, listed in Appendix E.

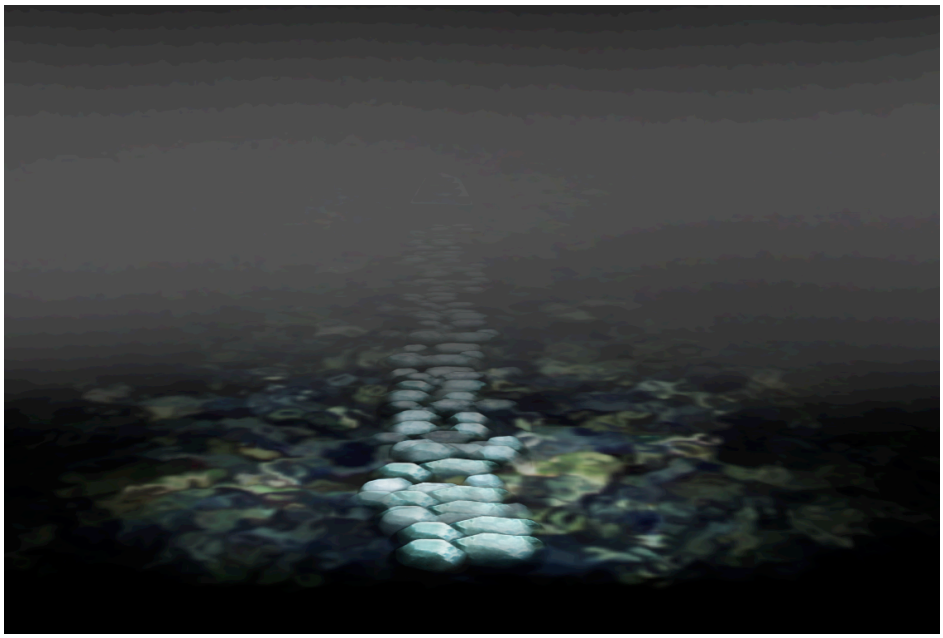


Figure 11. Example of Level 1 terminal visual feedback on lift success. Fog only clears given a successful lift.

Connecting real-time interaction to an offline summary using abstract, narrative content.

Like the AMRR system, the HAMRR system also uses abstract visuals to communicate performance; however in this case the visual content composes a scene, connected to a larger narrative thread arching across multiple levels of interaction. The design rationale behind using a path of rocks was primarily based on a path's linear form and directionality, from which deviation along any length of the path could be easily detected. Using a single line of rocks to communicate a path was avoided to deter the participant from trying to 'match' a singular trajectory to the target. Alternatively any segment of the path deemed as efficient was drawn with a bandwidth of around 2-3 white rocks per segment. The bandwidth was intended to suggest that an acceptable range or distribution of approaches to achieving an efficient reach exists (just as any variation in directionality within the non-impaired zone is deemed acceptable). Rather than fixate on the specific placement of individual rocks, the visual design was intended to direct attention to the general shape of the reach, manifested in the overall relationship among different types of rocks. Thus variation among the rocks' appearances (color variation and slight changes in shape) and slight noise added to displacement was used to both add visual interest and convey a sense of distribution.

While the path is a metaphorical representation of reach performance, the participant should be able to easily orient the feedback provided to his action in the physical space. The perspective of the scene, established by the rocks receding into depth, is reminiscent of the participant's view of the tabletop. The start of the rock path corresponds with the start location of the hand, while the end of the rock path corresponds to the target location, both of which are fixed in position. The terminal display does not appear unless the participant starts and ends from calibrated locations within an acceptable spatial zone. Thus a pair of white rocks is always fixed at the beginning and the end of the path to provide a frame of reference for the correct start and end of movement. The path was drawn in a single orientation going towards the middle of the screen, regardless of target location, to focus on the invariant aspects of performance, trajectory linearity or lack thereof.

Finally, color as a categorical descriptor of error magnitude was held consistent across the real-time color displayed by the target-embedded LED's and terminal feedback. The real-time visual feedback displays categories of error magnitude using white, yellow, or red to communicate performance that is considered efficient, with a moderate magnitude of deviation, or with a severe magnitude of deviation, respectively. If both horizontal and vertical errors occur simultaneously, then the maximum category's color between the two is displayed. This is held consistent in the terminal summary by coloring the rocks based on the greatest magnitude of error between components.

Composition, color palette and introduction of narrative. The focal point of the Level 1 scene is the path of rocks, drawn with high contrast in the center of the screen and leading the eye to the horizon line (often a focal point in traditional scenic representations). Scene components are rendered to have a moonlit effect, which, in conjunction with the ambient movement of the water and boat is intended to provide a calming effect for the participant to relax in the early stages of training. The color scheme of a scene with efficient performance includes blues, greens, and whites, while the color of rocks indicative of error are more garish and discordant with the water (reds, yellows). The remainder of the background is black to frame the scene, once again directing attention towards the path.

The path of rocks introduces the narrative concept of traveling on a boat used to connect various levels of training. In the Level 1 scene, the boat provides a goal at the end of the path, which corresponds to the position of the target. Reaching towards the boat as a destination also alludes to later stages in the narrative, in which the boat becomes the primary focal point. Several aspects of the scene are tied to its being the first level of a multileveled interactive narrative: shallow water by the coast contrasts with the deeper body of water in later levels; the setting at night changes into the daytime in the final level; and the perspective changes from observer to first person on the boat. Various elements change from being ambient aspects of the story to elements communicating performance, discussed later in this chapter. Currently the movement of

the boat and water are simply ambient indicators that the scene is live and mutable pending the participant's performance.

Fog is the mapping for the lift task because it was semantically congruent with the 'weather' feedback mapping used in Level 3 to communicate overall performance of a transport task. Both fog and weather pertained to visibility; a successful lift task elevated the fog from the scene just as successful Level 3 performance resulted in clear weather.

5.3.2 Level 2. During Level 2 interaction, the participant is evaluated after he performs a set of 5 repetitive reaches. The set of reaches is classified based on overall spatial performance of the hand (efficient, curved, segmented), timing of the hand (efficient, too slow, too fast, inconsistent), amount of torso compensation, grasp completion (total number successful of grasps), and/or lift completion (total number of successful lifts). The classification result determines the summary feedback the participant receives. Visual summaries communicate overall quality of spatial, grasp or lift performance, while an audio summary is used for overall performance with respect to timing or torso compensation. Feedback components for Level 2 are listed in Table 17. More information on how reaches are classified is provided in Appendix D. During Level 2 interaction, a white light is displayed on the base of the object to which a participant should reach to manipulate; no other feedback is provided. Once the participant completes the set of 5 reaches, visual feedback is displayed on the screen and/or audio feedback is played. See Video 4 for an example of a Level 2 interactive set.

The following sections describe in more detail how the visual summaries implemented by the author communicate performance and connects to the previous interaction level.

Table 17
Feedback mappings for Level 2

Quality of overall spatial performance	*Color and structure of boat (visual summary)*
Efficient paths	In-tact green boat
Mild Curvature	Yellowed, slightly distended boat
Severe Curvature	Reddened, severely distended boat
Mild segmentation	Yellowed, separated boat
Severe segmentations	Reddened, more separated boat
Quality of overall temporal performance	*Speed, instrument, fluidity of music (audio summary)**
Efficient timing	Musical progression with well-timed notes and pleasant, optimistic tone
Mildly slow	Somewhat slow musical progression, sad tone
Severely slow	Very slow musical progression, sad tone
Mildly fast	Somewhat fast musical progression, excited tone
Severely fast	Very fast musical progression, excited tone
Mildly inconsistent speeds	Somewhat inconsistent musical progression
Severely consistent speeds	Very inconsistent musical progression, erratic tone

Grasp completion	*Lantern light on boat (visual summary)*
Most grasps completed	Completely lit
About half grasps completed	Flickering
Few to no grasps completed	Off
Torso compensation	*Fog horn (audio summary)**
Amount of compensation above threshold	Fog horn present
Below threshold	No fog horn
Lift	*Amount of fog on boat (visual summary)*
Most lifts completed	Fog clears
About half lifts completed	Slight fog
Few to no grasps completed	Heavy fog
*Audio by Todd Ingalls	

Communication of performance in the visual summary feedback. The Level 2 scene displays the water and the boat that were introduced in Level 1. Each is shown with more detail given the viewer's closer proximity in the visual narrative. Similar to Level 1, the scene takes place at night, with a bright moonlit area illuminating the boat.

Level 2 training focuses on communicating overall movement quality across a set of 5 reaches, instead of providing detailed performance within a single reach as in Level 1. Movement quality with respect to spatial performance can be classified as efficient, curved moderately, curved severely, segmented moderately, or segmented severely. For each of these classifications, a pre-composed visual tag (or descriptive symbol) was designed to impart the

most salient aspects of the spatial classification. Each visual tag is represented as a uniquely drawn boat, of which the shape, color and texture communicate overall movement quality, displayed in Figure 12. See Video 12 for the animated examples of Level 2, listed in Appendix E feedback.



Figure 12. Level 2 Visual feedback summaries. (a) efficient, (b) no lift success, (c) mild segmented, (d) severe segmented, (e) mild curved, (f) severe curved, (g) grasp success, and (h) no grasp success.

The efficient visual tag is represented as a straight boat; the boat's surface appears smooth and painted a consistent green color. The curved tag is represented by a boat with bowed sides, resulting in an overall shape that appears distended in comparison to the efficient boat. On the moderately curved boat, the green paint is mostly covered by a yellowish tint, giving the boat a worn or aged appearance. The middle of each wooden seat is slightly broken as a result of the

boat's distention. The severely curved boat is more curved than the moderately curved one. The sides of its hull have buckled from what appears to have been a more extreme force expanding the width of the boat; the seats have completely separated and are left angled in different directions. A reddish rust-colored layer, giving the wood a rotten appearance, covers most of the boat's surface. The segmented visual tag depicts a boat that was broken into multiple sections, each of which is bobbing in the water separately. Each section is somewhat shredded at the location of which the boat was severed. Similar to the moderately curved boat, the green paint is mostly covered by an aged yellowish layer, giving the boat a decayed appearance. The severely segmented tag is also broken into pieces, but in this case the distance among segments is larger than the moderate tag, to suggest a greater amount of segmentation resulted. Similar to the severely curved boat, the formerly smooth green painted surface is covered in a red, rust-like layer.

For grasp completion performance, the overall scene was reduced in ambient light and a lantern was added to the top of the boat. If overall grasp performance across the set of reaches was successful, then the lantern was lit bright green. If performance were moderately poor, the lamp flickered, only periodically illuminating the boat. Finally if performance was severely unsuccessful, then the lamp was left unlit, resulting in a very dark scene. For lift performance, a layer of fog covered the scene, which could include any type of boat (e.g. a boat with or without a lantern depending upon whether training focused on grasp of hand spatial performance, respectively). If overall, lift performance across the set of reaches was successful, then the layer of fog quickly cleared, revealing the scene beneath. If performance was moderately poor, the fog only partially lifted to reveal part of the scene. Otherwise, mostly unsuccessful performance resulted in a layer of fog that obscures the entire scene.

Summary feedback that references previous interaction level. The Level 2 tags function as descriptive symbols, each of which concentrates the use of exaggerated stylistic elements (dark shadows, strong colors) and narrative elements (severely broken boats, lamp that illuminates darkness) to induce a particular affective response. Overall the style of the visual tags

was designed to be dramatic and slightly garish so that participants could recognize a tag relatively easily, and focus more attention on reflecting why a given tag was displayed.

Visual elements introduced in Level 1 were maintained in Level 2 to support the reductionist hierarchy and narrative arc. The yellow and red colors, indicative of error magnitude in Level 1, were used to communicate the severity of error in terms of either curvature or segmentation. Whereas before, shape was used to designate which section(s) of the reach had trajectory error (as a local event), shape in Level 2 communicates the cumulative effect of performance across multiple reaches, expressed as damage to the boat. To communicate grasp performance, the green lantern on top of the boat references the green success light for successful manipulation in the Level 1 real-time interaction. The fog element, used to communicate lift performance, was directly maintained from Level 1. In this case, to maintain form coherence, the prominent aspects of training significantly change their mapping across different levels of interaction (e.g. path performance, speed performance) while more auxiliary aspects of performance (e.g. lift performance, torso compensation), measured similarly across levels, are kept similar.

The use of color as an indication of error magnitude thus far connects levels, to facilitate connections between remembered rock paths (in which the error was easily discoverable) to boat shapes (in which deciphering error requires more contemplation). To also help facilitate a new perspective of the visual feedback as a summary of multiple actions, the boat, which shifted from an ambient element in Level 1 to the performance indicator in Level 2, was rotated to a three-quarter angle, to support a new perspective by the onlooker of the scene that is different from the centralized view. Finally, the summary feedback in Level 2, unlike the summary feedback in Level 1, was sometimes paired with an audio summary of temporal performance if training was focused on both time and space performance. Level 2 therefore also represents an intermediate step between Levels 1 and 3, the latter of which integrates audio and visual feedback into a single audiovisual scene to communicate overall efficiency of spatial-temporal performance, discussed in the following section.

5.3.3 Level 3. During Level 3 interaction, the participant performs a multiphase task that consists of either a sequence of 2 simple tasks or a transport task. At completion s/he receives feedback on the overall efficiency of the performance. A single rating of efficient, moderately impaired, or severely impaired is assigned based upon an overall efficiency measure that combines scores for total reaching time, number of speed phases, and overall path ratio. Feedback on manipulation of each target, which was evaluated in a binary manner depending upon if the participant made sufficient contact with the target in the correct order, was communicated as the presence/absence of an island per target location. Compensation, evaluated on the approach phase of the task only, was communicated in the same manner as in Level 2. More information on assessment measures driving the feedback is provided in Appendix D. Table 18 summarizes the feedback provided in Level 3. See Video 5 for an example of a Level 3 interactive set.

The following sections describe in more detail how the animation implemented by the author communicate performance and connects to the previous interaction levels.

Table 18
Feedback mappings for Level 3

Overall Efficiency	*Weather and ambient sounds and/or music**
Efficient	Clear blue sky, calm water, calm wave sounds (if transport, smooth travel with relaxing music)
Mild	Grey sky, medium waves in water, creaky sounds (if transport, slightly shaky travel and foreboding music)
Severe	Stormy, lightening sky, rough water, storm sounds (if transport, rough travel with distressing music)
Manipulation success	*Discrete visual indicator*
Success	Island visible
Miss	No Island visible
% Torso compensation	*Fog horn (audio summary)**
Above threshold	Fog horn present

*Audio by Todd Ingalls

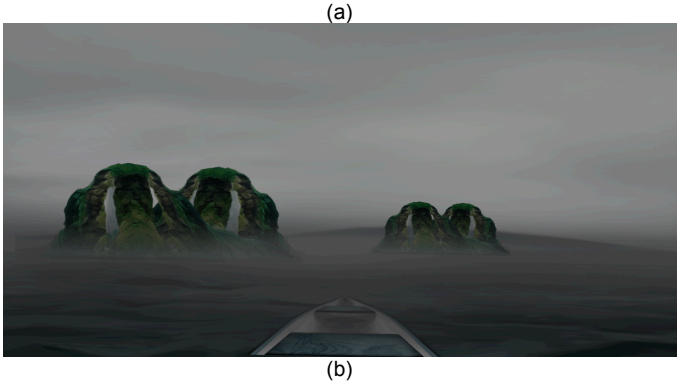
Communication of performance in the audiovisual summary feedback. The scene displays a large body of water, a sky, and two islands during the daytime. The edge of the boat present in previous levels is visible and intact, centered at the bottom of the screen. The horizon line is located towards the center of the scene and fluctuates slightly, providing a point of view that is similar to a first person point of view from the boat.

The goal is to produce a scene with conditions most suitable for travel. Efficient performance produces a sunny, clear day with calm water. Both the sky and water are bright blue. Moderately impaired performance produces an overall grey environment. Visibility is decreased with fog and heavy clouds moving across the sky. The water is also much darker, and waves are slightly bigger than shown in the efficient case, resulting in more fluctuation on the boat. Severely impaired performance produces a heavy rainstorm with lightening. Visibility is further reduced with rain and larger waves cause further fluctuation on the boat. Figure 13 summarizes examples of scenes with different performance results.

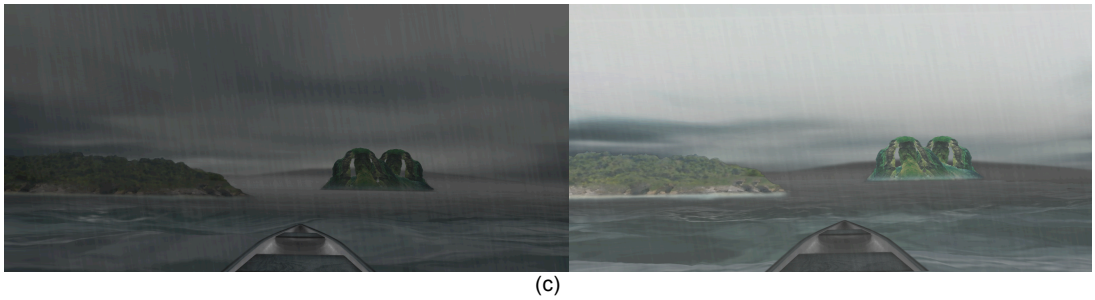
Feedback on target manipulation is provided in terms of the presence or absence of an island. The type of island reflects the target type used in the task. A simple flat island corresponds to the flat touch target object; a slightly taller island with more vegetation corresponds to the button target object; and a tall island with the most elaborate shape and brightest color corresponds to objects to be grasped, such as the cone or portable transport object. Given that there are always a pair of adjacent target locations for each Level 3 task, the location of the island indicates the order of interaction: the island that appears closer to the boat reflects the target object that was approached first during execution of the task, while the farther island reflects the target approached second. The islands on the left and right of the screen correspond to the relative position of the adjacent targets in physical space. The target located in either the left or middle position on the table corresponded to the island on the left of the screen, while either the middle or right target location corresponded to the island on the right of the screen. See Videos 13 and 14, listed in Appendix E, for a more detailed view of the feedback provided for sequence versus transport task



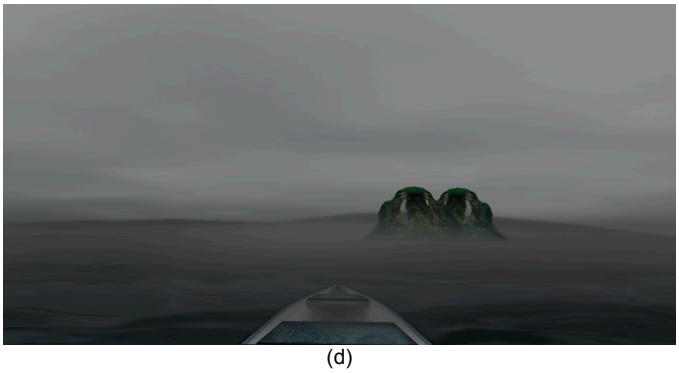
(a)



(b)



(c)



(d)

Figure 13. Example stills of Level 3 visual feedback. (a) Efficient flat object to flat object sequence task, (b) moderate transport task, (c) severe button to cone task (left before lightening, right during lightening), moderate transport task.

Feedback scenes provided for sequence versus transport tasks differed in the following ways: For a sequence task, the boat remains stationary and the scene is displayed for the duration of 4 seconds. The audio feedback (designed by Todd Ingalls) consists of ambient environmental sounds, which range from calm waves washing against the boat for efficient performance to more creaky rigid sounds for impaired performance. For a transport task, the scene is extended to 8 seconds to show the boat travel forward past both islands. In this case the audio feedback consists of music mixed with the ambient environmental sounds, which range from melodic and calming for efficient performance, to eerie and foreboding for worsened performance.

Culmination of lower levels. Communication of efficiency (or lack thereof) is narrative-driven (e.g. the favorable weather conditions are desired so the boat can travel easily). The visuals and sound function as a cohesive unit, as they would in film or other audiovisual narrative, to convey a mood or shift in plot. The narrative's setting has changed to daytime to suggest that the participant has advanced to a higher stage of training. Whereas previous visual environments were stationary, the intent of providing a first-person travel scene was to impart a rewarding sense of movement that also semantically aligns with the physical task of moving an object between two locations. Figurative imagery (using an avatar for example) was intentionally avoided to help immerse the participant in a first person point of view without introducing new and potentially distracting elements within the story. Level 3 is further discussed in terms of its relationship to previous levels using a narrative structure and reductive hierarchy, presented next.

5.3.4 Connecting the three levels using a narrative arc, reductive hierarchy and two dimensional-fading. Each scene can appear in any order based on the desired training goals, while still contribute to the overall narrative thread. Training complexity results from increasing the cumulative difficulty of tasks trained each day, which can in turn, result in different variations of the feedback (e.g. a participant's performance triggers only efficient feedback for the button touch task, but triggers negative feedback for the grasp cone task) thus altering the course of the narrative thread. Regardless of the training path that a participant experiences or the nature of

the participant's deficit, the feedback was designed such that each variation of a scene can still be placed within the overall narrative thread, and communicate the direction towards improvement. Visual elements of the story link experiences across levels and are used to help facilitate the participant's memory of performance across different levels of training.

A limited number of story elements were used to build the visual narrative thread in an effort to help the participant manage the number of components that required tracking. Figure 14 identifies each element as either performance-based (mutable based on performance) or ambient (agnostic to performance but contributes to the scene). Elements are reusable in that they can crossover from ambient to performance-based. For example, the boat in Level 1 is unaffected by performance yet provides the goal for creating a path of rocks; versus the boat in Level 2, which is shaped based on overall performance of a set of reaches. Almost all scene elements are present in each level of training (boat, water, sky) or have some allusion to components in later levels (e.g. the stone path in Level 1 versus the islands in Level 2, the implication of the beginning of a journey in Level 1 that is realized in Level 3). In Levels 1 and 2, individual elements within a scene are performance-based, whereas in Level 3 all components of the scene integrate to produce a scene communicating performance. Elements ultimately merge (in narrative function) to contribute to the goal of taking the trip.

In parallel to the narrative structure, a reductive hierarchy was used to connect performance mappings across the three activity levels. The reductive hierarchy helps connect individual visual features (color, shape) of performance-based narrative elements across levels to help facilitate learning through associations of explicit assistive feedback with more high-level suggestive feedback. The semantics of color established in the real-time interaction (red is severe, yellow is moderate error magnitude) is maintained in the Level 1 and Level 2 summaries. While magnitude of error is communicated similarly, the resolution of error information (e.g. direction, spatial or temporal related) is slowly reduced over levels. Ultimately, in Level 3 performance is communicated as an integrated scene, thus semantic use of color and shape are applied differently in Level 3 to produce a more natural environment. Figure 15 summarizes the

use of mappings to form a reductive hierarchy. While some mappings change across levels, others are held constant to help balance overall complexity. For example, mappings for lift performance and torso compensation, both auxiliary aspects of performance secondary to path and timing of the hand, are used consistently across multiple levels, communicated as the fog and foghorn, respectively. Finally, Level 3 displays movement while the previous levels show stationary scenes (aside from the ambient animation of the water and rocking boat), which further differentiates the transport task from previous repetitive training.

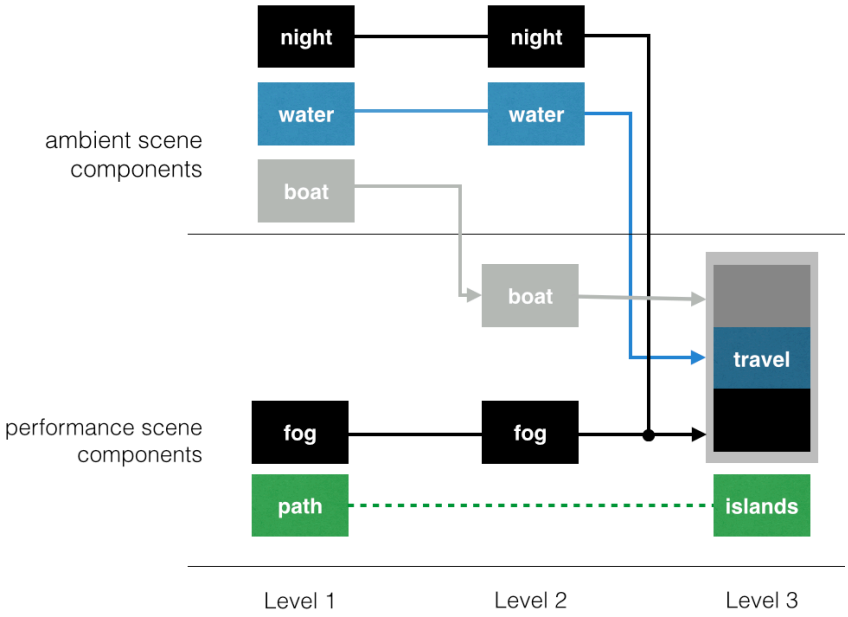


Figure 14. Performance and ambient components build a narrative thread.

While multi-leveled feedback aims to gradually increase the amount of self-evaluation by the participant, two-dimensional fading aims to balance complexity along three dimensions of design: activity, meaning and time delivery, to make the experience more manageable for the participant. A conceptual representation of two-dimensional fading is shown in Figure 16. Performance of individual reaches is paired with assistive feedback delivered concurrent to movement and summarized immediately after. In Level 2, the activity structure is similar to Level 1, in that the participant is completing repetitive training of simple tasks. However Level 2

feedback is delivered in summary form after all 5 repetitions are complete. Level 3 trains the most complex tasks; while the feedback is semantically the most complex (spatial-temporal performance is combined into one efficiency evaluation delivered in narrative form), the time before a participant receives feedback is reduced in comparison to Level 2.

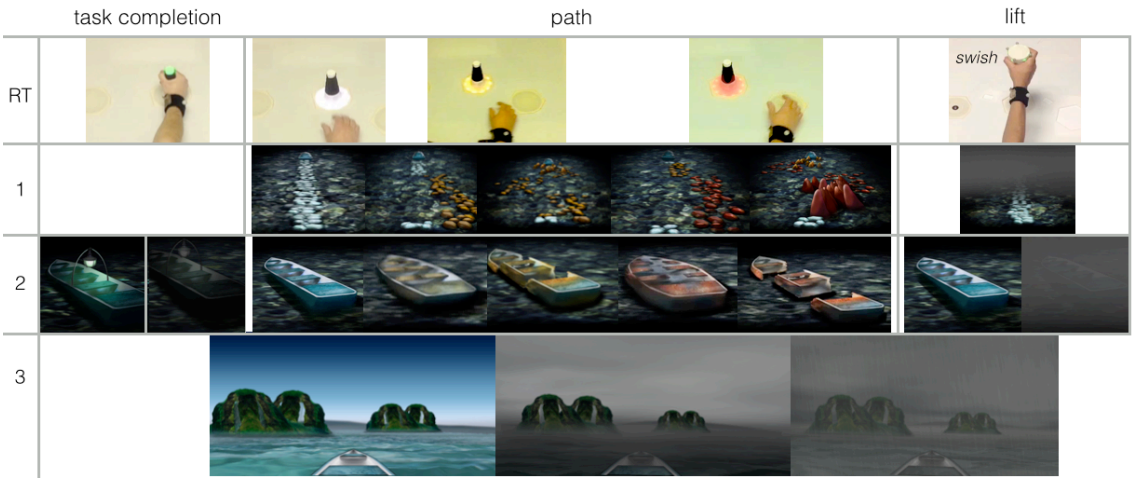


Figure 15. Use of visual mappings to form a reductive hierarchy. Not shown: representations of audio feedback, which also followed a reductive hierarchy structure.

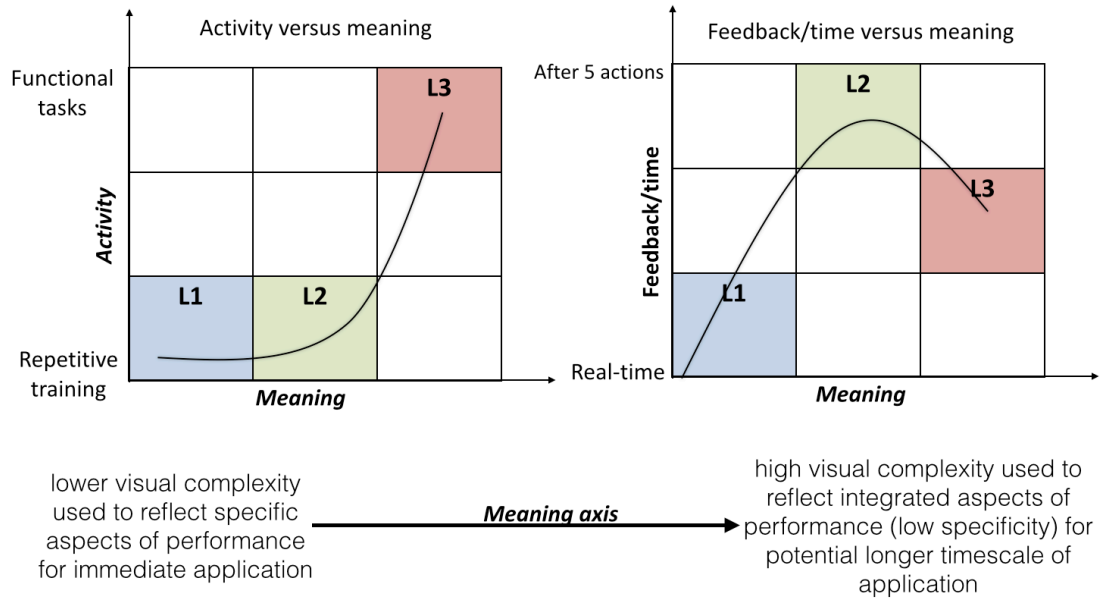


Figure 16. Two-dimensional fading over time and meaning across activity levels. L1, L2, and L3 denote Levels 1, 2 and 3, respectively.

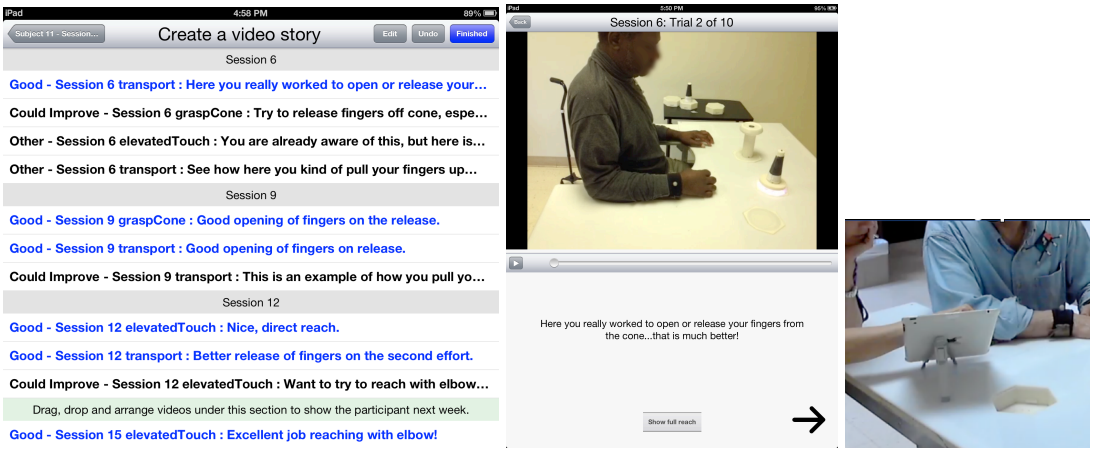
5.4 Video Stories for Assisted Reflection

Video stories, composed by the physical therapist, provided a summary of patient performance over longer timescales than the home-based AMRR system's feedback and were shared with the participant once each week of unsupervised training. Training monitoring meetings were designed to provide the opportunity for semi-structured interaction between the therapist and participant, in which the therapist collected video of the participant performing tasks (without augmented feedback), recorded the participant's perspectives on his progress, and then shared videos (in the form of video stories) from previous weeks.

An iPad application was designed to guide the therapist in administering such meetings and provide a portable means for composing feedback outside of immediate interaction with participants. The videos recorded each week provided a bank of raw material from which the therapist could select videos and/or identify themes from across multiple weeks of training (a timescale not addressed by the feedback) to illustrate changes or maintenance in performance within or across tasks. Used in conjunction to training, the training monitoring meetings were also designed to help the participant fill in gaps left by unsupervised training. Discussions spurred by

the video feedback covered aspects of movement not explicitly addressed during interactive sessions and provided strategies for both future training with the system and activities at home.

To create a video story, each week the therapist reviews a series of videos recorded of the participant performing different tasks: reaching to grasp a cone, reaching to touch an elevated target and transporting an object with/against gravity. The therapist segments these videos into individual reaches and then tags those that could potentially demonstrate “good” performance, performance that “could improve”, or “other” for another aspect of performance that is notable. Each video that is tagged can also be annotated with text. Tagged videos are then presented from all past session on an editable list (Figure 17a), of which elements can be reordered or deleted as needed to provide a summary appropriate for the participant.



(a) (b) (c)

Figure 17. List of bookmarked videos for composing a video story and sample view. (a) Selected videos can be re-arranged from prior weeks. (b) Videos are then strung together based on the story composition shown in (b). (c) Therapist shows and discusses videos with the participant.

Examples of two resulting feedback stories are summarized in Table 19 and Table 20, which list the tasks, tags and comments from video stories composed for Subjects 7 and 2, respectively. Frequently mentioned aspects of movement for a given participant are listed with an arrow pointing up or down, depending upon whether the therapist was providing positive or corrective feedback, respectively. Common themes emerged across several stories that are also evident in these examples: The therapist often selected from multiple types of tasks to provide

feedback. A story always began with a positive tag and comment to either demonstrate improvement or a movement aspect already being performed well; then if applicable videos demonstrating aspects that could improve were presented. The therapist seemed to focus on key aspects of movement (as expressed in the comments) across different weeks of training; issues were re-addressed across weeks to show improvement or worsening, and were rarely only mentioned once. However video stories provided in Tables 19 and 20 remained within sessions, in that the therapist only selected and ordered videos tagged from the previous week. Comparisons between videos were facilitated by alternating 'good' video trials with 'could improve' video trials, coupled with the therapist specifically asking the participant to notice a key difference between two. Another common theme across video stories was the dominant discussion of movement aspects that the system did not specifically address with feedback: such as manipulation, jerkiness, and elbow extension. In addition to showing the video, the therapist would sometimes also follow up by showing the participant how to execute movement or demonstrate using the participant's arm. Finally, examples below also provide specific strategies were recommended for the participant to try in the following unsupervised session and in some cases at home.

Table 19

Summary of features from video stories composed for Subject 7 (all videos shown were from previous week)

Shared on week 2

Tag	*Task*	*Comment*	*Path*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Transport	Here you really worked to open or release your fingers from the cone...that is much better!				↑
Could Improve	Grasp cone	Try to release fingers off cone, especially first two fingers.				↓
Other	Elevated touch	You are already aware of this, but here is a visual of how you use your trunk to reach the button instead of reaching with your elbow.		↓		
Other	Transport	See how here you kind of pull your fingers up off cone.				↓

Shared on week 3

Tag	*Task*	*Comment*	*Path*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Grasp Cone	Good opening of fingers on release.				↑
Good	Transport	Good opening of fingers on release.				↑
Could Improve	Transport	This is an example of how you pull your hand up and off the cone instead of opening fingers to release the cone.				↓

Shared on week 4

Tag	*Task*	*Comment*	*Path*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Elevated touch	Nice, direct reach.	↑			↑
Good	Transport	Better release of fingers; try to extend elbow more and move trunk less.		↓		↑
Could Improve	Elevated touch	Want to try to reach with elbow more.		↓		

Shared on week 5

Tag	*Task*	*Comment*	*Path*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Elevated Touch	Excellent job reaching with elbow!		↑		

Table 20
Summary of features from video stories composed for Subject 2 (all videos shown were from previous week)

Shared on week 2

Tag	*Task*	*Comment*	*Steadiness*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Grasp Cone	Nice path, good grip, minimal ataxia (jerkiness)	↑		↑	
Good	Elevated Touch	What you are doing well here is isolating movements....not moving trunk during reaching and accomplishing task with elbow reaching and grasping only.		↑		
Other	Elevated Touch	What we see here is a subtle unsteadiness of the hand that device is not sensitive enough to pick up....I think you can still think about minimizing the unsteadiness during training however.	↓			
Other	Elevated Touch	See previous note trial 3 - I let the video run a tad longer to see unsteadiness when returning hand to resting place.	↓			

Shared on week 3

Tag	*Task*	*Comment*	*Steadiness*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Elevated Touch	Less wavering noted on this trial.	↑			
Could Improve	Elevated Touch	A bit of wavering noted with reach.	↓			
Could Improve	Grasp Cone	More ataxia noted on this reach than previous ones.	↓			
Could Improve	Transport	High to low - A minor problem releasing grip of first transport.				↓
Other	Transport	Low to high - compare to other release of object.				
Other	Transport	Low to high - fairly steady while transporting object.	↑			

Shared on week 4

Tag	*Task*	*Comment*	*Steadiness*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Grasp Cone	Good opening of fingers both directions.			↑	↑
Good	Transport	Fingers open nicely anticipating grasp....a little waver in path direction.	↓		↑	
Good	Transport	Steadier path with this reach.	↑			

Shared on week 5

Tag	*Task*	*Comment*	*Steadiness*	*Trunk/ Elbow*	*Grasp*	*Release*
Good	Grasp Cone	Good release of all fingers from the cone.				↑
Could Improve	Transport	This is a good example of how your release is different with the cone vs the cylinder. As we discussed, you thought this was due to the unstable base of the cylinder as opposed to the width of the cylinder.				↓

Because the video stories are provided a week or more following performance of the actual task, the use of direct representational media is appropriate. This balances the provision of feedback at greater timescales than those given in training and the potential comparison across tasks. Providing the participant with a side view of his/her performance while he is tending to a task directly in front of him also facilitates a new perspective he otherwise would not have (e.g. if the participant were trying to perform a task at home in front of the mirror the result would be different as he would be splitting attention and/or might have to position himself facing the mirror).

5.5 Summarized Application of Interdisciplinary Concepts for Unsupervised Training

The three levels of visual feedback provided by the home-based AMRR system use abstract representation to facilitate understanding of spatial aspects of movement performance. As levels progress, feedback changes from assistive, provided concurrent and terminal to the action, to suggestive, being delivered in summary form following the action. Metaphorical content that relates to a story is used to engage active participation in connecting real-time performance to the summary feedback. While the visual stream is used in conjunction to audio feedback streams (provided on hand speed and torso compensation), multiple streams of information are also provided within the terminal and summary visual feedback itself. Primarily color is used to communicate magnitude of error while shape is used to communicate direction/nature of error. Visuals are embedded in the physical space for concurrent feedback and switched to the screen for offline contemplation, utilizing a mixed digital-physical space. The use of a multileveled

narrative to help aggregate different experiences with the feedback across individual trials and sets has been discussed in previous sections.

Coaching is primarily used in conjunction with the training monitoring application, which provides a summary of direct representational feedback to facilitate reflection. The therapist highlights information for both passive consumption but also sometimes asks the person to actively think about what they should do in a given scenario. The therapist as the coach is also facilitating aggregation by summarizing movement from previous trials and connecting themes from previous weeks with the current week.

Instructional content was also provided to give directions on how to perform a new task and utilize the feedback (example shown in Video 2). The instructional content balances the use of predominantly abstract metaphorical content by using direct representation of a participant performing the task. The media is designed for passive consumption and prescriptive application, provided before the participant tries a task. Figure 18 displays the relative placement of different types of visual media on a continuum for function, participation, time delivery and representation.

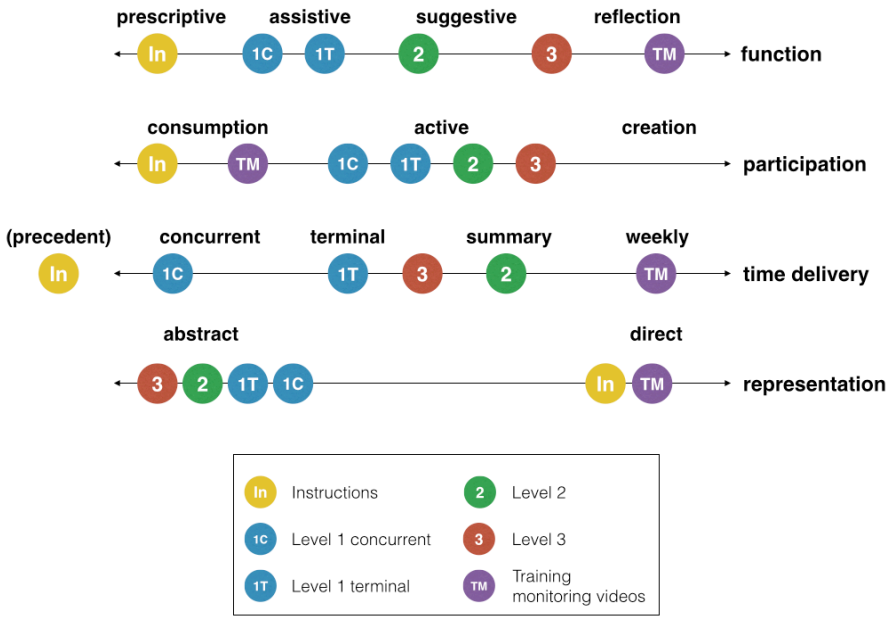


Figure 18. Overview of relative application of concepts for home-based AMRR. Relative placement of three levels of local feedback on performance, training monitoring video stories for reflection, and the instructional content along axes of function, participation, time delivery and representation.

CHAPTER 6

IMPLEMENTATION PROCESS

This chapter highlights different aspects of the implementation process used by the author for the visual trajectory summary in the clinical system, the home system visual feedback environment, and the training monitoring iPad application. Given the author's background in visual arts prior to working in INR media design, examples are provided to demonstrate in part how an arts-based perspective was applied to develop the compositional framework, in conjunction to experience gained working on the systems with the AMRR group.

First insights from developing visual summaries used for the clinical and home-based systems are presented. While both of these summaries are paired with real-time information they are discussed differently in terms of how they complement the real-time feedback, given that the amount of detail provided in the real-time feedback differs between supervised and unsupervised training experiences. Next the designs of visual summaries of repetitive tasks and complex movements are discussed from the Level 2 and Level 3 feedback of the home-based AMRR system. Here discussion focuses on how visual concepts were used to summarize movements in a more abstract manner than the feedback providing performance displays discussed in the previous section. The overall structure of the training monitoring application for assisted reflection is presented, the design of which needed to enable the clinician to both collect data and compose feedback for the participant. Last software implementation of these components is discussed in terms of high-level considerations for drawing and communicating with the other system components during interactive sessions with participants.

6.1 Designing a visual performance display summarizing real-time interaction

Visual summaries that complement real-time interaction (i.e. cases in which participant input produced concurrent feedback) were developed for both the clinical and the home-based AMRR systems. While both summaries are displayed following the performance of an individual reach with real-time feedback, and therefore share some aspects of design strategies applied, they also differ in function and design approach.

6.1.1 Designing a visual summary that reduces concurrent information. Iterative sketching, in conjunction with experiencing the clinical AMRR system first-hand, observing stroke survivors interact, and consulting with more senior members of the team, helped prioritize design constraints that led to the summary's final design shown in Figure 19(g) and Figure 21. Iterating on different sketches provided a means for determining which visual aspects were more or less successful in communicating trajectory performance. Below are examples of resultant insights, paired with sample sketches in Figure 19 to demonstrate visual concepts in application.

The trajectory summary for the clinical AMRR system needed to fit within the existing context of the real-time feedback environment developed by the AMRR team prior to the author's joining: particles coalescing on the screen to form an image. In addition to intuitively communicating hand deviation in real-time, an imparted sense of accomplishment and progress informed the bases of the real-time feedback's aesthetic design (e.g. visually pleasing forward movement of particles, successful resolution of the image). While these aspects were critical for motivating a stroke survivor to advance an affected limb forward, the summary's primary function was to reduce this experience to aspects of the reach that need to be adjusted for the following attempt. Thus *only aspects of the activity on which the participant should focus in the summary were visualized*. In the limited amount of time a participant has to view the summary, visualizing the entire activity (such as in Figure 19(a)) could lead to focus on extraneous information instead of aspects of performance the participant should explicitly adjust for future movements. Showing efficient parts of the movement also might infer that a single solution exists when in fact some variation within and across reaches is natural and not reflective of impairment.

A previous method for summarizing trajectory error (implemented prior to the author's contribution) tinted and froze (or fixed the location of) errant particles over the course of the reach. While the result of this method was both aesthetically pleasing and conceptually fit well within the existing interaction, the summary often would obscure real-time performance information with previously frozen particles (e.g. if error were made in the beginning of the reach it would hide particle movement later in the reach). The timing of error was also only discernable at

a coarser level that desired. Thus a key insight revealed from this design was to *display the summary following the activity's completion*. Separating these phases of interaction would eliminate the visual overlap while also provide the participant an opportunity to focus on using the concurrent versus terminal feedback information separately. Given the assumption that the visual summary should be displayed following the real-time interaction, new design challenges emerged with respect to designing visuals that complemented the pre-existing real-time experience.

The existing perspective used in the real-time feedback was a hand-centered coordinate system to help participants focus on the magnitude and direction of error in a consistent manner no matter the location of the reaching target. As shown in Figure 20, this meant the participant was seeing deviations from what one would consider the perspective of his hand. Early sketches representing a different point of view (such as Figure 19(a) which illustrates a first person point of view of the table) resulted in a disconnect between the real-time experience and summary. Deviating from the point of view constructed in the real-time virtual space (mapping between performance and visual point of view) could lead to unnecessary or confusing additional visual transformations that may impede utilization of the summary feedback provided on the same display (e.g. by not facilitating connections between the real-time feedback and summary information). Thus *consistent points of view were maintained between real-time interaction and summary.*

The fluidity of the real-time interaction and the change of image size reinforce a sense of depth and perspective. However a static summary can fall short of communicating depth if a frame of reference is not imposed (similar to how a rendering of a city landscape uses change in size among buildings and perspective lines that converge at a point at the horizon to articulate depth). The summary should compensate for this lack of real-time information by emphasizing perspective lines and exaggerating depth. In other words one should *impose a structure reflective of the space's perspective*. The sketch shown in Figure 19(b) begins to accomplish such a structuring of space by using perspective lines that converge towards the center of the image.

The events highlighted in the summary should be discernable and measurable at a glance. The summary is essentially a filter of the continuous movement, such that it only highlights major trajectory error events. While the small size of the particles are conducive to communicating continuous movement in real-time, larger individual markings are more easily assessed as discrete events. Furthermore when building a perspective space, small marks offer less contour (outside border) to skew and insinuate depth. The sketch shown in Figure 19(c) appears to have a flattened space, demonstrating how more continuous small markings are less successful in establishing both a defined sense of depth and location of error than the sketches in Figure 19(b) or Figure 19(d). Discretizing depth into "steps" also helps summarize the overall timing of the reach (e.g. if error happened early, in the middle or towards the end). While the overlap between markings gave the summary a more continuous feel, the sketch of Figure 19(d) was deemed confusing given some of the earlier markings faded into later markings.

Particle size, shape, and color do not necessarily need to be maintained in the post action summary if using these visual features compromises the design's functionality. Thus one should *seek a balance between stylization and maintaining visual continuity with real-time visuals*. For example, representing trajectory error as particles better suits the aesthetic continuity between real-time interaction and summary, but the particles' form poses challenges in fulfilling some of the goals outlined above. While effort should be made to maintain the visual vocabulary that is established in real-time (e.g. consistent perspective space, use of geometric shapes, location to communicate direction, and size to communicate magnitude of error), the visuals should cater to the new context of the summary even if full aesthetic continuity is compromised. Another example can be found in the real-time interaction's frame of reference: the rectangular size and shape of an image intuitively communicates error as either horizontal or vertical components. In the case of the trajectory summary, the presentation of error in summary form was reconsidered as a circular space. Horizontal and vertical error can be easily composited to draw an arc, which also maximizes the screen space available to draw given that the image is static and screen space is limited. Curvature also offsets the lack of continuity in depicting

discrete events in static form. Compare the circular space used in sketch in Figure 19(e) with the rectangular space of Figure 19(b). Also red coloration was also favored over using the color palette of the source image (as shown in Figures 19(b,d,e)) to provide a better indication of the markings as error.

Finally user-testing revealed an additional frame of reference could potentially help participant's place error during their initial exposure to the system and trajectory summary. An early non-interactive version of the design, such as the example in Figure 19(f), was tested with non-impaired users to determine if participants could comprehend the direction and magnitude of error of various error cases. Three series of images were shown. Cumulative score was measured to determine if participants improved their understanding over time. Across the 5 participants, relative magnitude was the easiest aspect to perceive correctly, while timing was the least successful. The confusion in comprehending timing was likely influenced in part by not interacting with the system, however when the error space was described as a series of concentric rings, participants expressed more understanding. Thus in the final implementation, a grey static space of rings shown in Figure 19(g) was added to the visualization in case participants using the system experienced any confusion. When this grey space is enabled, if the participant makes a reaching error, then red bars replace the grey bars at the location of error. This option was sometimes used to provide an introduction to the space and then turned off later once participants were more familiar with the meaning of the red bars' configuration.

Several of the insights gained from designing the trajectory summary informed the development of the rock path summary for the home system, namely that feedback for INR can vary in functionality and delivery over time to facilitate different perspectives of movement performance. Similar to visual or music compositions created for arts-based purposes, no aspect of feedback functions in isolation and consideration for the entire feedback environment should influence local design decisions for a particular feedback component.

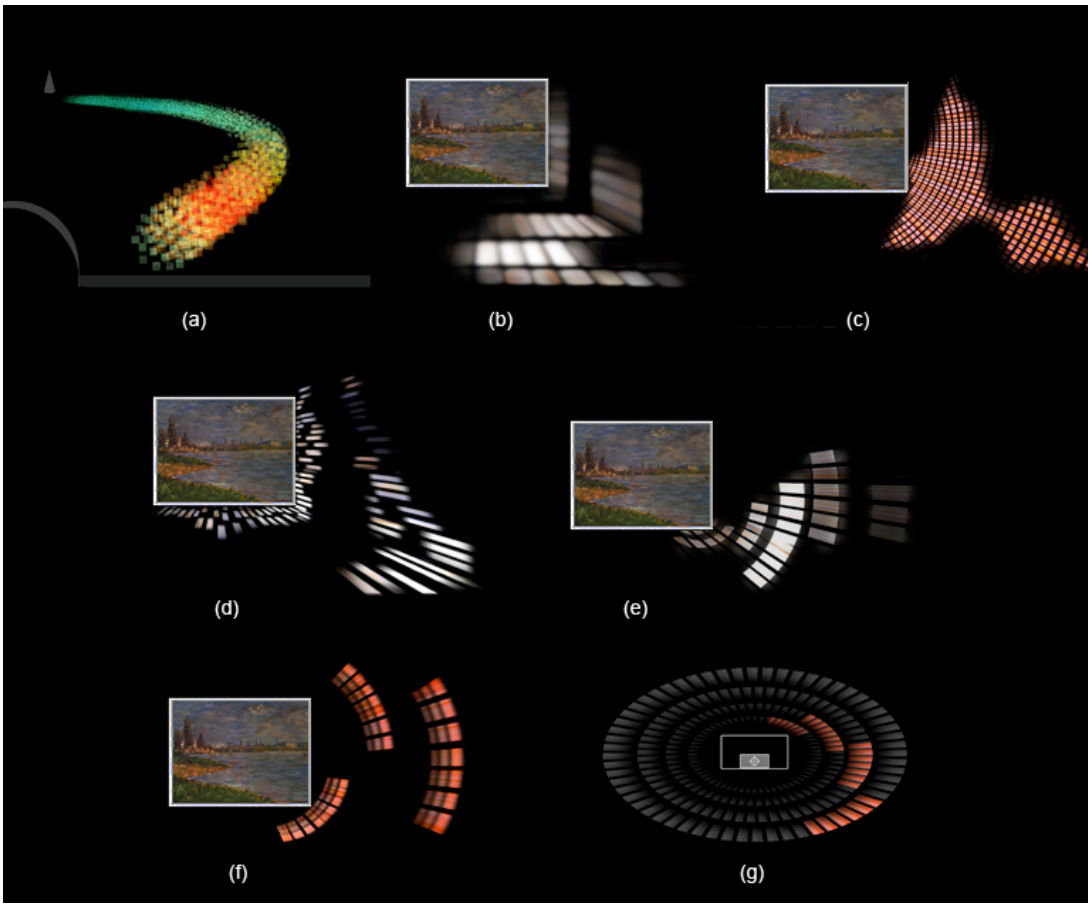


Figure 19. Iterative sketching for the AMRR terminal trajectory summary

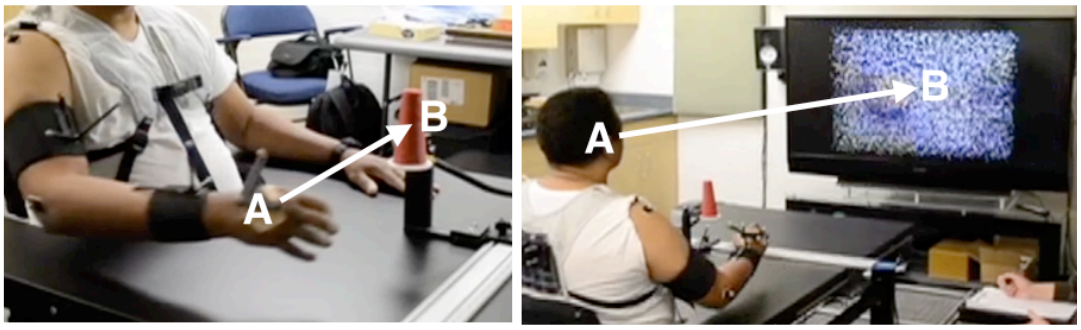
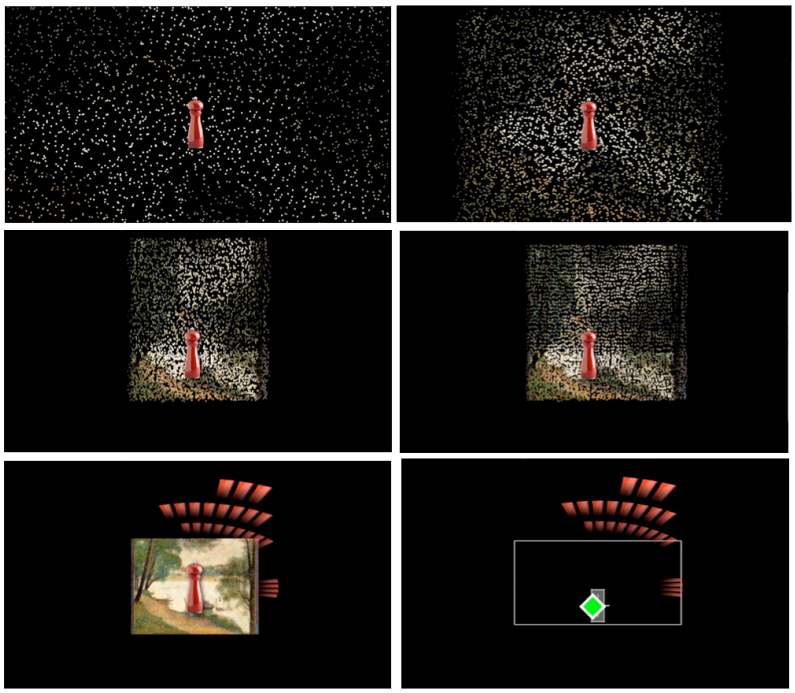
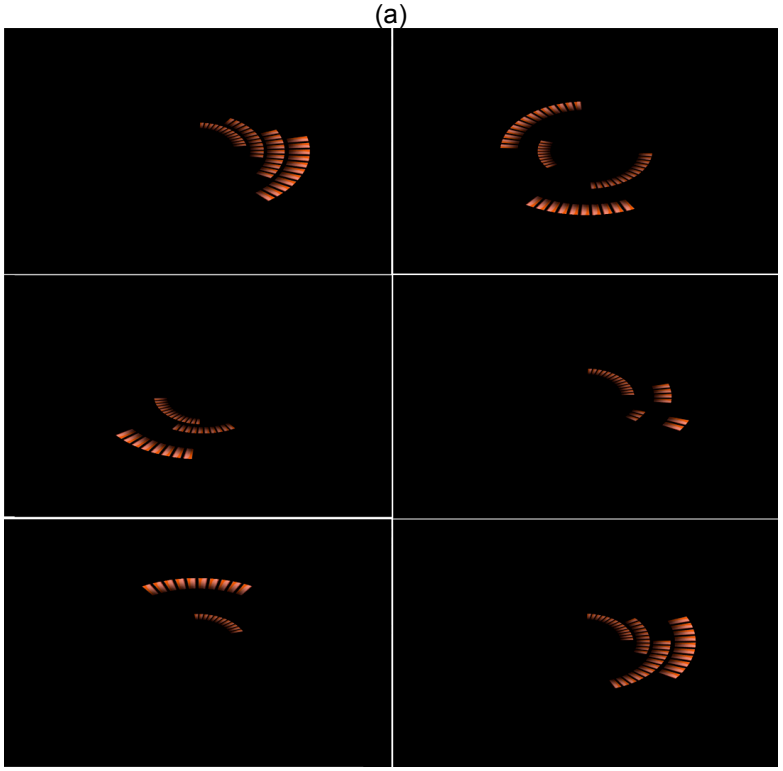


Figure 20. Hand-centered point of view used in the clinical AMRR system



(a)



(b)

Figure 21. Additional examples of clinical AMRR summary feedback. (a) Shown with snapshots of the real-time trajectory performance feedback from the clinical AMRR system. Order of images goes from top-left to bottom-right. (b) Other potential error

6.1.2 Designing a visual summary that augments concurrent information. The visual summary designed for Level 1 training in the home system was displayed following coarse concurrent feedback on spatial error: while the participant was reaching, light feedback provided in the base of the target object communicated the extent of deviation. No indication was provided on whether this deviation resulted from horizontal or vertical error to give the participant the opportunity to determine the direction for improvement based on peripherally monitoring the position of his hand during reaching. The visual summary displayed on the screen, after movement was completed, visualized not only the magnitude but also the direction of error to encourage the participant's use of more detailed summary information.

A challenge inherent to reducing real-time interaction to a static offline summary is that some information must be lost in order to communicate a given performance element at an effective resolution. *Information needed to be reduced to a resolution that supports the goals of the summary*. In comparison to the real-time color feedback, the rock path both needed to summarize information (communicated as maximum errors across 20 segments) but also provide more detailed information on performance by including the direction of error. While the full reach was sampled by the analysis software at 50 segments to determine the real-time color provided on the base of the target object, the resolution of twenty segments was determined to be the appropriate number of segments that could be used to convey the overall shape of the reaching trajectory, given the size and distance of the display from the training table.

Perspective is reminiscent of physical space given real-time feedback is not screen-based; however some dissociation with physical space was still required. Without real-time onscreen visuals, it would likely be more difficult to significantly deviate from the physical perspective (yet still facilitate an intuitive association between physical and digital spaces) given that there is no real-time interaction to establish a new visual transformation. Whereas previous design iterations changed the direction of the rock path depending upon the target location (Figure 22) to assist the participant in mapping the path to the physical space, user testing revealed that altering the direction of the path compromised clarity of error location and extent

depending upon the target location. Users who perceived misalignment between the drawing and their reaching movements were distracted, given that the location of the path had to change with respect to the participant's midline (sometimes the start was to the right of the midline, sometimes the start was to the left) to maximize screen space. Thus, the path was drawn in a single orientation going towards the middle of the screen, regardless of target location, to neutralize these effects and help further shift attention to the overall shape of the movement. Iterating on the direction of the path demonstrates that even in the case of using abstract (non-representational) media, the correct level of dissociation from the physical space required fine-tuning in practice.

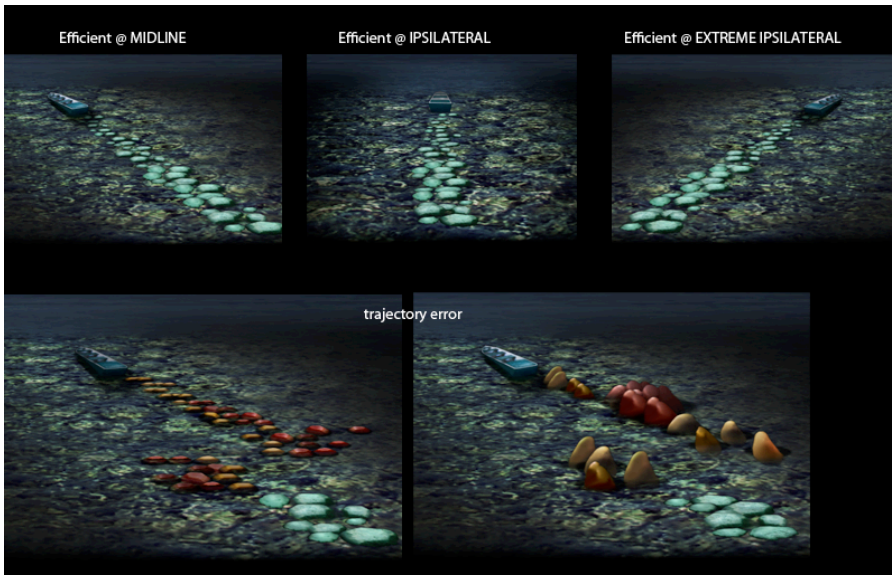


Figure 22. Example of previous iteration of path design which transformed the start and end locations based on the physical target location.

As previously mentioned, introducing variation to the rock path was intended to focus a participant's attention on the overall shape of the path rather than specific placement of rocks. Each time feedback is drawn for a reach trial the textures used to draw the rocks are selected at random from a designated color set, depending upon the category of performance. Each rock texture within a set was designed with a slightly unique shape or coloration. However *variation needed to be bounded so it does not detract from communication of the performance signal*. Each rock color still needed to be easily associated with the corresponding color of the table light. Noise added to the displacement of the rocks, to slightly vary locations among different reaches,

needed to fall within acceptable bounds of the actual error magnitude, such that variation did not make the error look noticeably smaller or larger. See Figure 23(a) for examples of bounded variation for the color sets and deviations. Figure 23(b) provides a conceptual overview of how the path was drawn combining the error signal with the variation.

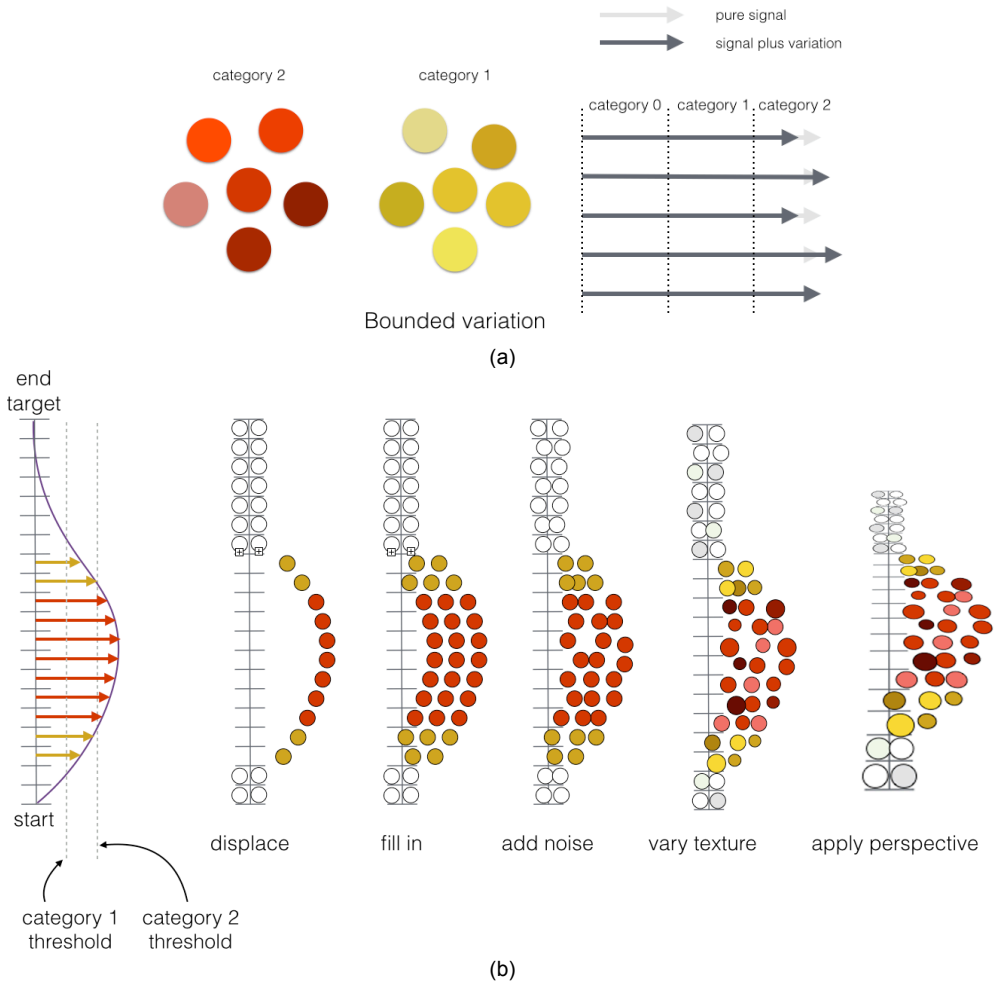


Figure 23. Combining variation with performance signal. (a) Color and deviation were slightly varied for visual interest and more natural variation. (b) Example of how path was drawn by applying transformations based on performance plus added variation (does not reflect actual drawing order).

When designing the rock path, *information needed to be scaled such that mappings would hold in any combination of performance elements*. For both real-time (e.g. particles in the clinical AMRR system) and summary visual feedback presented on a screen, analysis values need to be scaled to translate performance error into drawing coordinates that fit within the limited

screen space. For example horizontal error needs to be rescaled into drawing coordinates such that rocks do not shift off-screen. However introducing randomized aspects for visual variation in a static summary requires different considerations than real-time visual feedback presented on the screen: information continuously updates in the real-time case while the history of the entire performance accumulates in the summary case, causing visual overlap. Thus the summary case also requires consideration of the interaction across different mappings. As an example, the maximum drawing values required scaling such that the largest vertical error rocks do not excessively obscure other sections of the reach; while the minimum drawing values for vertical or horizontal errors needed to be scaled such that they were visible at any segment along the path, especially given that a perspective function was used to progressively shrink rocks that are farther in distance. Testing various combinations of scaling minima and maxima, while scaling information in between, is necessary.

The design of the negative vertical error required additional iteration in comparison to the other horizontal and vertical error mappings. Communicating the magnitude of negative vertical error in the same manner as the positive vertical error (increasing height of the rock, but facing downward into the water to indicate a negative deviation) was ineffective given that more often than not, other rocks occluded the drawing. Ultimately magnitude of pure vertical error (with no horizontal component) was not communicated in favor of holding consistent the mappings that worked for the majority of other error cases. Instead pure vertical negative error was rendered as very dark (close to black) rocks that appeared deep underwater, with similar distortions applied to the rock texture as was used to render the water. If these rocks were paired with horizontal deviation they were tinted yellow or red based on the category or horizontal error.

6.2 Designing a visual summary abstracting performance

In contrast to the summaries used for performance display, the visual summaries for Level 2 and Level 3 in the home system were designed to abstract performance across repetitive actions and an individual complex action, respectively. In these cases, the semantics of the visual

content itself is used in part to communicate performance. For the Level 2 summary of repetitive actions, examples of how visual concepts were developed and tested are discussed. Then for the Level 3 visual summary of a complex action, the extent to which mappings should deviate from Level 1 and Level 2 (of the reductive hierarchy) is presented. Secondarily, the examples of feedback used in Level 2 and 3 illustrate that, as one increases the level of abstraction, a greater reliance on prior experience composting visual scenes was used, and thus a greater number of viable solutions likely exists for these types of feedback. Solutions presented here demonstrate one approach given the context of the story of traveling on a boat.

6.2.1 Iterations on concept and testing for a summary of repetitive movements. Before the development of the rock path in Level 1, the concept of using a boat was originally intended to show performance of individual reaches. The rationale was the boat's simple, fairly linear form, and its potential to integrate within a larger narrative. Before testing interactively, hand drawn sketches of distortions applied to the boat appeared to be an intuitive way of communicating inaccuracies in the reach, with examples shown in Figure 24. However, testing this concept interactively revealed several limitations in using a slightly complex form for assistive feedback (e.g. the boat lacks a homogeneous surface on all sides, representing both vertical and horizontal error was difficult). The slightest combination of errors to the boat's form resulted in a distortion that was ultimately confusing and could not be decoupled easily. However stylized sketches did suggest that the imagery could lend itself to high-level characterizations of movement, rather than attempting to directly reflect an individual movement.



Figure 24. Example preliminary sketches for the visual tag summary concept.

Thus the use of the boat as a symbolic representation of performance was tested to see if it could convey an overall quality of reaching movements. Based on prior experience with the clinical AMRR study, the home system team selected multiple movement quality tags that could be used to describe common impaired reaching movement performance characteristics and consulted the supervising physical therapist from the AMRR clinical study (S.M. Liu, personal communication, June 8, 2011). The following tags were selected for the predominantly spatial performance based tags: (1) curvature (non-linear reach with trajectory error), (2) segmentation (non-continuous reach with abrupt segmented motion denoted by changes in direction, often associated with lack of joint asynchrony), (3) tremulousness (shaky hand movement while reaching), (4) incompletion (reach was not finished or required a hook-like movement at the end of the reach); and for the time-based tags and (5) reaching too fast, (6) reaching too slow, (7) hesitant reach (initial lag of movement, sometimes associated with segmented movement), and finally (8) reaching with inconsistent speeds.

Once tags were selected, images were composed for the spatial tags and audio composed for the time-based tags. Only the development of the visual tags by the author is discussed here. For each spatial tag, a representative boat was drawn with exaggerated characteristics suggestive of the movement (similar to a caricature of the movement). For example, a highly warped boat that appeared to have been distorted by erratic movement represented tremulousness. However, there were multiple visual aspects that could be used to communicate the visual tags. For example, a particle effect could also be suggestive of shakiness. Thus a user study was conducted to determine (1) which variant, if any, of a group of visual designs was most successful in communicating a given tag and if (2) any visual designs were associated with more than one tag. The goal was to select visual designs that were correctly paired with a unique visual tag.

Ten non-impaired participants were randomly assigned to one of two groups: group 1 matched audio or visual feedback to descriptive tags while group 2 matched the tags to the feedback. Participants were seated in the home system and asked to perform 5 normal reaches

to a cone to have a reference for the movement they were asked to associate with the efficient verbal descriptor (our baseline for comparison). Then, before beginning the matching task, the participant was shown the ideal visual form, the efficient boat, which is the feedback a user would see after completing a reach with no measurable errors.

A subject, from group 2 for example, was then presented with a list of the descriptive tags and a feedback example designed to represent the information contained in the tag; and instructed to select which tag or several tags s/he feels best represents the image. Each participant matched no more than 20 visual examples. A subject of group 1 engaged in the same procedure except matched one of several images to an individual tag.

Figure 25 shows the tags that were evaluated with corresponding results (not shown is the incomplete tag which faded towards the end of the boat, which yielded 75% correct responses). Each pie chart is titled with the intended tag, the dominant visual element being used, and the percentage of answers assigned to each tag. A plus next to a tag category name indicates that it was not a unique answer; in other words the participant chose a category with one or more other categories as well to identify the image. Because the tags are intended to be non-overlapping categories, only answers that were correctly identified without the plus are indicated as a desired response.

Visual features were repeated across multiple images to determine which feature was most associated with a particular tag. For example, breakage (or the fragmentation of the boat into shards) was used in boats intended to communicate curvature, segmentation and jerkiness. Particles were also used for both incomplete and jerkiness. Results demonstrate that breakage was often associated with segmentation, even if it was located towards the end of the boat to indicate incompletion. This suggested that participants were sensitive to the high-level visual characterization, rather than just the location of the breakage being connected to location along the reach. Particles on the other hand, were both strongly associated with tremulousness and incompleteness when rendered at the end of the reach. The design that received the greatest mix of responses was the curved boat with the breakage visual element. Among the examples, this

boat seemed the most realistic in terms of its wreckage. Examples that seemed to be the most clear (were correctly identified by the most number of responses) were those that did not look realistic, such as the particle effect. Segmentation was strongly identified with the idea of sections. Stretching of the boat was strongly identified for curvature.

Based on these results the two designs that were chosen were the segmentation tag communicated as separate sections of the boat, and the curvature tag communicated as curvature symmetric about the boat's longitudinal axis. The symmetrically curved boat, while slightly less successful in communicating curvature that the curved right and curved vertical boats, was selected for the final design because the curvature classifier, as an assessment measure, ultimately did not discriminate among left-, right-, or vertically-dominant curvature. Thus the design that was most successfully labeled but also agnostic to direction was chosen. While other designs seemed effective in communicating other tags, such as tremulousness, they were ultimately excluded from Level 2 training due to the associated difficulty in reliably classifying these tags using the reduced sensing infrastructure provided by the system.

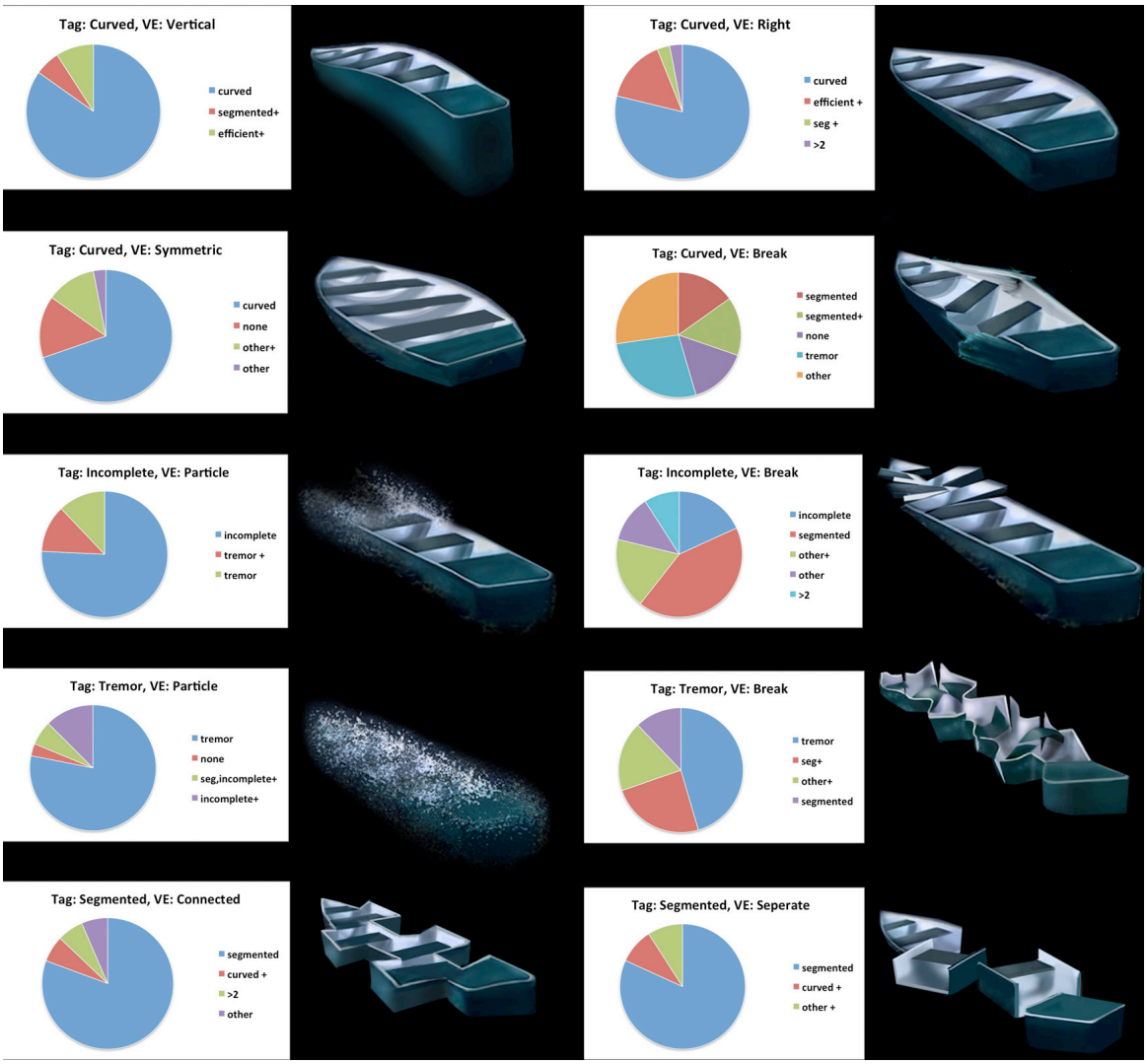


Figure 25. Visual tags and corresponding results from the non-impaired user study matching visual tags to verbal descriptors.

6.2.2 Iterations on concept for a narrative summary. Whereas in Level 2 separate modalities were used for spatial versus temporal performance (temporal performance not discussed), in Level 3 all aspects of performance were integrated into one efficiency measure. The guiding design constraint used was, if semantics of the movement assessment are integrated, the feedback environment should also use an integrated representation to parallel the activity structure. Defining the extent of integration in visual terms however required some iteration.

Initially the extent to which mappings should be abstracted from previous levels was not readily apparent. For example, Figure 26(b) used a red haze to communicate poor performance, while sketches in Figure 26(e) and Figure 26(f) used the color green embedded as light in the sky (similar to an aurora borealis effect) as a measure of success. A weakness of this approach was that color (as used in this context) was not semantically coherent with the narrative, as it did not "affect" the quality of traveling (which was used to communicate the transport).

The idea of "transfer" was also explored in other ways besides only showing the boat travel. For example, one animated sketch, from which stills are shown in Figure 26(c, d), had the viewer follow birds taking off from one island and landing on another; the birds only reached the second island if the transport was efficiently performed. However, this approach introduced a new narrative element that was unnecessary, potentially difficult to see, and could furthermore be misleading: the concept of a distribution was already used for performance display feedback in Level 1. Introducing a flock of birds might suggest that performance was being directly tied to their flock shape, just as the spread of rocks was tied to trajectory, which is not desirable given efficiency is being communicated as a single rating.

Similar to extending the use of color, initial sketches of the islands attempted to extend the idea of a green light indicating success (an artifact of lower level training) by placing a lighthouse on the island representing a cone and green lights embedded in the flat island representing the touch object. These more literal connections were ultimately deemed unnecessary since at higher stages of training it was assumed that the participants could make

easier associations given their experience with the system. Islands were thus rendered with a somewhat more natural looking aesthetic and once again performance was communicated on a very coarse level: presence or absence of an island was used to communicate success, so that performance information was visible at a glance.

Weather ultimately was chosen as a means to communicate performance as it affected all aspects of the narrative and the visual scene. The concept of color was changed to represent a natural scene, reflecting an intentional departure from previous use. While greens and blues were embedded within scenes of efficient performance, the grey overcast sky was used as an broad indicator that performance was either moderate or severely inefficient. Furthermore, because a complementary soundscape was also used, the visuals carried less of a burden in communicating distinct categories of performance, given that the sound coupled to the visuals further differentiated the three scenes.

While likely several solutions to high-level narrative summaries exist, the final design was selected because it reflected a true departure from earlier mappings in the hierarchy, which was desired given that training shifted from simpler repetitive tasks to complex tasks. Given the iterative nature of experiential media system design (e.g. analysis components were introduced or dropped throughout the design process) it is important to select content with both compositional and semantic “breathing room”. When components were added to training mid-development, the feedback environment was able to support these additions because the content was flexible. A natural environment, travel, and passage of time are examples of themes that can be adapted in either very literal or abstract directions. By identifying a core theme of travel with the core activity of the home-system of transporting an object, auxiliary aspects (e.g. adding a lamp on the boat for Level 2 grasping, adding fog for the lift component) were more easily introduced than if the visual environment were highly specific (as can sometimes be the approach used in more traditional gaming).

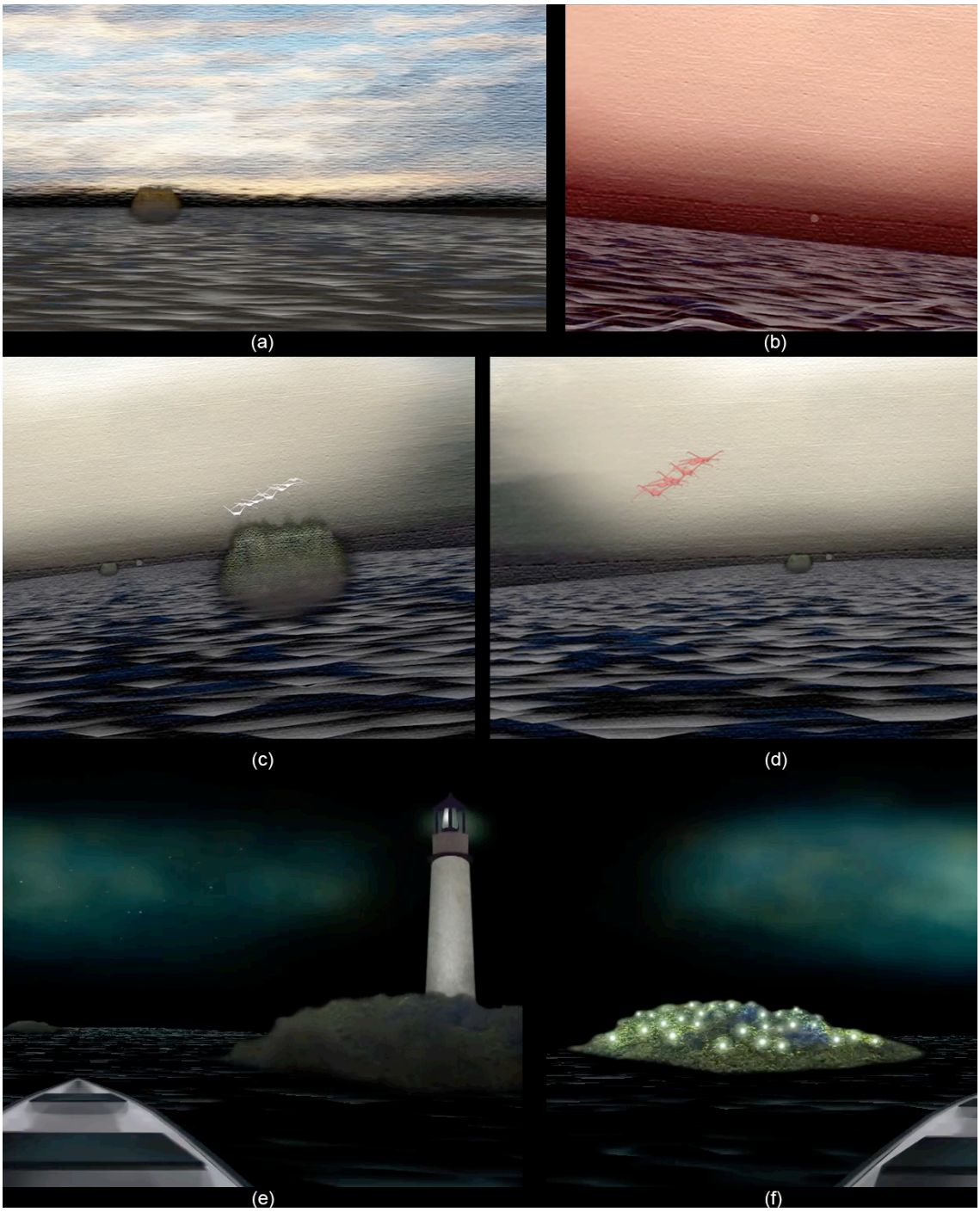


Figure 26. Iterations on concept for the Level 3 Summary

6.3 Tool for composing media for assisted reflection

The following sections describe how the training monitoring application was designed to provide the therapist with an interface to both capture information from the participant and compose feedback on his performance. Interaction needed to be designed such that the information was easily exchanged between the therapist and the participant.

6.3.1 Administer the training monitoring tasks. The training monitoring application first guided the therapist through a series of steps to ensure video was collected in a consistent manner across subjects, sessions and tasks types. For each task, task setup and instruction to the patient are provided for the therapist to read aloud or use as reference. When video recording, the app checks that the iPad is in a predetermined orientation, otherwise a warning is given to rotate the tablet accordingly. When video recording an outline of the table is provided in the camera's view to help the therapist ensure the camera is at the correct distance and angle with respect to the table and participant (see Figure 27). The iPad was also fixed to a tripod during recording to ensure a stable capture. Once recorded, each video is automatically linked with a given subject, session, and task type identification, and then appeared in the filmstrip preview. If for any reason an error occurred, previously recoded videos (only by the app) can also be linked to a specific task if needed as well. The four tasks captured include the transport up, transport down, elevated touch, and cone grasp tasks to capture a range of movement across both simple and complex, trained and semi-trained tasks.

6.3.2 Administer system experience questionnaire. The system experience questionnaire was developed by the author to gain a better understanding of the participants' training experience. Participants were asked to provide a response to multiple choice questions related to the amount of therapy, enjoyment using the system, ease of its use, challenge of tasks, ease of using feedback to understand performance, enjoyment of feedback, extent to which the affected arm was used outside therapy, overall feeling during the week, and amount of energy and mood before and after therapy. For each of the multiple-choice questions, therapists could provide more information by annotating the participant's response in an additional text box. If the participant

replied negatively (e.g. I somewhat disliked using the system) then annotations elaborating on the selection were required before the questionnaire could be marked as complete. Multiple-choice responses were on a 5-point rating scale. Following completion of 12 multiple choice questions, the participant was asked to describe in his/her own words how s/he believes s/he is doing in training, which the therapist typed into the app. This final free response question was included in case other questions did not adequately capture any aspect of the participant's experience that he would like to share. An example item is shown in Figure 27e.

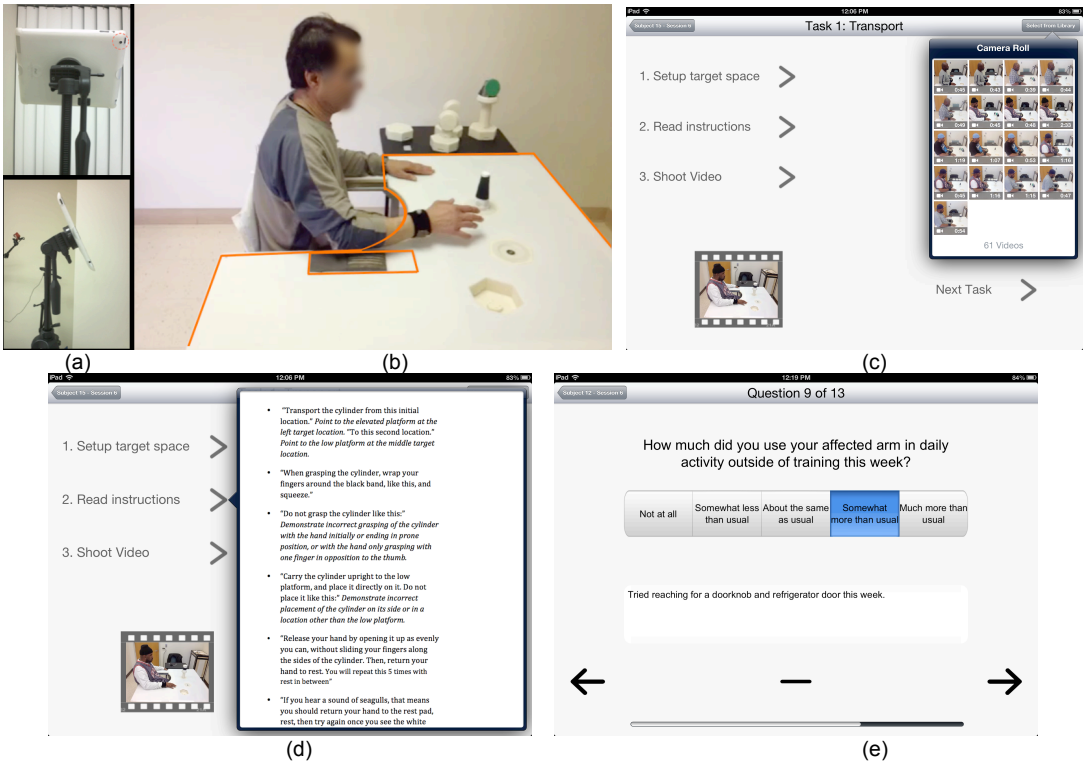


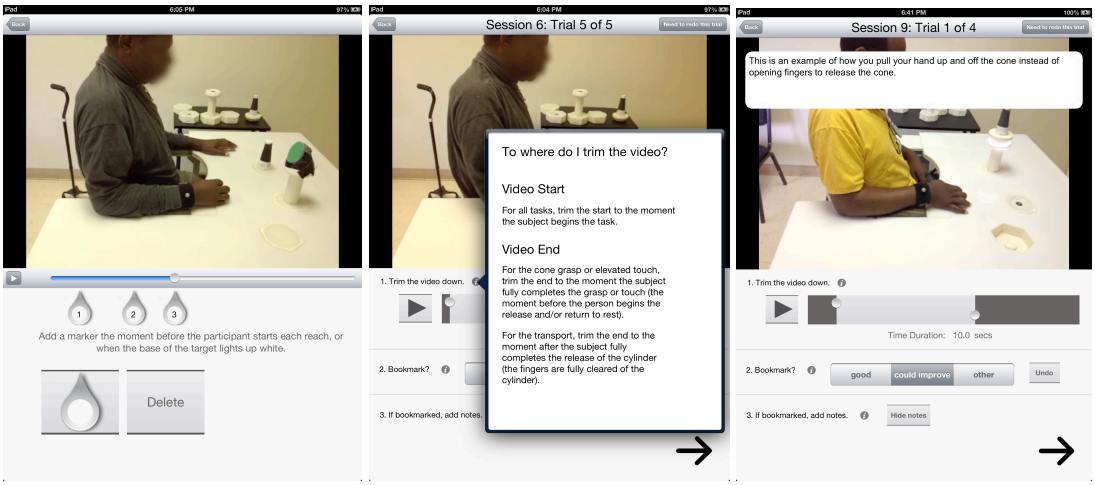
Figure 27. Tablet setup and sample views from training monitoring app. (a) Physical setup, (b) Capture view with overlay to help positioning, (c) Task view with optional video library and (d) instructions, and (e) sample item from questionnaire.

6.3.3 Segmentation and tagging of videos. Each video that was recorded contained a set of multiple reaches. Videos were segmented into individual reaches to facilitate the therapist's assessment of an individual trial in order to provide feedback to the participant (tagging and annotation). Videos also were segmented so that, when the therapist rated trials at a later date, only the part of the reach that should be rated was considered (e.g. return phase was not considered for rating). Therapists were asked to segment the videos they recorded following a training monitoring meeting. Segmentation was broken down into two steps, coarse and fine. For coarse segmentation of each video, the therapist was asked to add markers near the beginning of each reach, before or at the appearance of the white light go prompt. After markers were placed to determine the beginning of each reach, the video was segmented into individual trials, for which the start of one reach was used to determine the end of the previous. For the last trial the end of the video was used to mark the end of the reach.

Then, fine segmentation, tagging, and annotation of each coarsely segmented trial were completed in parallel, as each requires more careful review of the video. A two-sided slider was provided to finely trim down the video based on more specific task-dependent requirements (e.g. the transport task videos required segmentation that included the release while the cone task videos were segmented to end at grasp completion). The remainder of the reach, which contained the return and was not desired for rating the videos, could still be used to show to the participant aspects of his/her performance later. This full reach feature was added based on the therapist's request because the release of an object and/or return sometimes showed improvement or worsening of movement quality. The duration of the finely segmented reach is also displayed for the therapist's consideration in case time to completion influences the therapist's tag and annotation. See Figure 28.

Following segmentation, the next section asks if the therapist would like to add a bookmark. The information button explains that a video should be bookmarked if the therapist would like the option of using it later to compose the video story. A reach can be tagged with 'good', 'could improve', or 'other'. Finally the last section asks if any other notes should be added

to the video. These notes are visible to the subject later if they accompany a bookmarked video within a final video story.



(a) (b) (c)

Figure 28 Segmentation and annotation. Example views from (a) coarse and (b,c) fine segmentation steps. (c) Bookmarks and annotations were added following fine segmentation.

6.3.4 Create story for next week. After segmentation is complete for the three task videos recorded for a week, the application unlocks the step to create a video story. Each week produced a total of 5 reach to grasp cone trials, 5 elevated touch trials, and 4-10 transport trials (depending upon the session), among which only the trials that were bookmarked appear for in the story composition view (Figure 17a). Once the edit button is turned on bookmarked videos across all sessions can be sorted in any particular order by dragging them from their respective session groups to the editing group. Videos can also be deleted (or restored) from the list to assist the therapist in choosing what to use. Each page in the video story shows the video, plus the comment, plus an option to show the full reach. Videos can be selected directly from the list or traversed using the arrows on each view. The list of videos is saved to the following week's training monitoring meeting in the app to present and be a source of discussion with the participant the following week. Figure 29 provides an overview of the steps from capture to creating the video story.

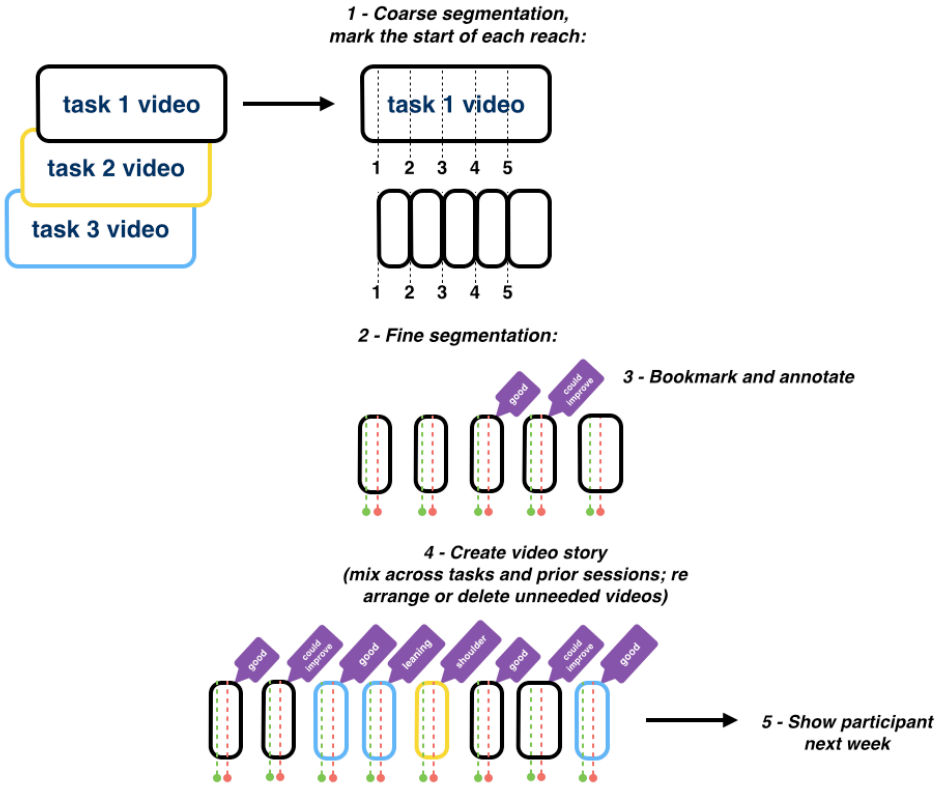


Figure 29. Overview of video segmentation, tagging and annotation used to compose video stories to show the participant at subsequent training monitoring meetings.

Finally, after the application's evaluation in practice, the amount of time required to complete both segmentation and story composition should be reduced to minimize the time required of the therapist outside of therapy. More automated approaches to segmenting the video (such as determining the start and end of movement based on timestamps recorded by the system) should be used to provide more time for the therapist to focus on story composition.

6.4 Software Implementation Overview

The trajectory summary and the visual feedback for the home system were each implemented as a plugin, a software component that adds functionality to a larger program *Dash*. Dash is a Mac OSX program created by AMRR team member Loren Olson for the modular development of interactive environments. Dash also provides an application program interface for drawing using OpenGL, a software development kit for drawing graphics.

6.4.1 Time of display. The visual feedback summaries were triggered to display following the completion of the movement. For the trajectory summary in the clinic, the visuals were triggered to display at the onset of the grasping phase, which begins after the system registers a successful grasp by the participant. The summary then remained on the screen for the participant to review while s/he returned his hand back to rest, after which the system entered a randomized intermittent period of time in between trials for the participant to rest. The visuals faded at the conclusion of this rest phase. In the home-system the visuals were triggered following the hand's return to rest, given that more detail was provided in these summaries and more time was required for contemplation. Furthermore since the participant was focused on the physical space (the location of real-time visual feedback) the participant was encouraged to focus on one phase of action at a time, that is to complete the return, and then look up at the screen for feedback.

6.4.2 Communication with other plugins. Analysis and system control information were received from other programs for feedback drawn for both the clinical system and home-based system. As an example, Figure 30 shows an overview of communication between the visual feedback and other plugins of the HAMRR system. The visual feedback plugin for the home system was responsible for drawing all visual content presented on the screen by responding to inputs from two external plugins, adaptation and analysis (implemented by Michael Baran). The adaptation plugin controlled the current interaction state, which the visual feedback translated into the display of specific content. The analysis plugin provided the visual feedback plugin with analysis feature values used to render the performance-related feedback. The visual feedback plugin in turn alerted the adaptation plugin as to when an animation or movie finished so that the

next chain of system commands were appropriately timed. Messages were also sent by the visual feedback plugin to the audio feedback plugin (implemented by Todd Ingalls) in cases for which audio information needed to be synced with an internal state of the visual feedback animation.

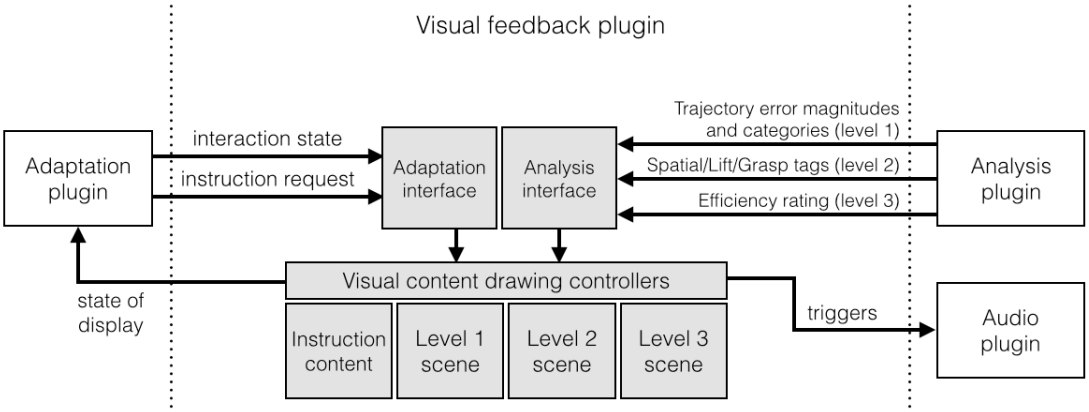


Figure 30. Overview of communication between the visual feedback plugin and other modules in the HAMRR System.

6.4.3 Other technical notes. All feedback components were drawn using custom textures (images) designed and/or photographed by the author; otherwise textures used were modified open source photographs. An emphasis was placed on rendering detail of forms in 2-dimension as much as possible, while 3-dimensional elements were used for the implementation of waterscapes, placement of scene objects, and perspective using of virtual cameras. Waterscapes and underwater rocks were drawn using shader programs, which allow for rendering effects to be calculated on the graphics processing unit (GPU). Wave effects were achieved by applying transformations based on a combination of oscillator functions and a noise function from ("Noise Function", 2012). Custom oscillator functions were used depending upon the effect desired for the water environment (e.g. Level 1 was calmer while Level 3 produced rough waves for the stormy environment). The color or intensity of waves was also manipulated based on height of displacement to achieve a simple shimmer effect.

A combination of noise and oscillator functions was also used for the lightening and flickering light effects. Fog and rain were drawn using multiple overlapping textures with different fading timers that cycled. The rain sheet textures were overlapped in alternating patterns to produce an effect similar to a moiré pattern when animated to also help give a sense of depth.

Finally the Training Monitoring application was developed as a native IOS application for the iPad. All images used were drawn or digitally manipulated from open source images by the author. Assistance on implementing video capture and editing was primarily obtained from the Apple developer site.

CHAPTER 7

EVALUATION IN APPLICATION

In this chapter conclusions are drawn on the extent to which evidence collected from the clinical and home-based AMRR studies supports the application of the compositional framework for INR media design. Conclusions are organized in terms of confidence level, in which evidence supported by both studies is presented first, followed by more nuanced exploration into potential ways to evaluate the feedback's effect on movement quality. The chapter closes with more qualitative observations from the clinic and unanswered questions to be considered in future re-design of the visual media.

7.1 Acceptance of Mixed Reality Training Using Abstract, Multi-stream Feedback

For both the clinical and home-based systems, stroke survivors were able to train across environments with variable amounts of digital immersion, ranging from tasks with multiple feedback components enabled, to no augmented feedback provided. Ability to complete a task was not hindered by the absence of some or all feedback components despite having previously been exposed to a task with one or several components enabled. Furthermore, in the case of the home-based system, participants were able to complete multileveled training, which altered both the amount and type of feedback depending upon the structure of the activity (e.g. individual, group of repetitive, sequence of tasks, or transport).

The acceptance of multi-stream feedback was also evident in both the evaluation of the clinical and home-based AMRR systems. Spatial performance of the hand was communicated in the visual feedback, while timing aspects of the hand and intermittent aspects of body level performance were communicated using audio feedback. Participants were able to utilize multi-stream feedback provided both concurrent to movement and in summary form following movement. While the extent to which movement quality performance uniformly improved differed between systems, participants from both systems did improve in multiple aspects of performance, each of which was mapped to individual feedback components. The collective evidence from the

application of AMRR systems suggests that complex feedback covering multiple aspects of performance can be applied effectively to therapy.

While the definitive number of streams is unknown and context/participant dependent, Table 21 lists the number of audio and visual streams used for the population trained by AMRR systems in both supervised and unsupervised contexts. In both systems only one prominent visual stream and one prominent audio stream were provided in real-time (concurrent to movement), over which other intermittent sounds or visuals were layered. Participants in the AMRR system tended to train with potentially up to 5 streams of feedback (e.g. continuous visuals, continuous sound, 2 body performance sound indicators, success sound) depending upon the training focus designated by the therapist.

Table 21
Summary of feedback streams trained in AMRR

Time delivery	*Movement feature*	*AMRR*	*HAMRR*
Concurrent	Hand trajectory	Prominent concurrent visual stream	Prominent concurrent visual stream
	Hand speed	Prominent audio stream	Prominent audio stream
	• Torso • Shoulder • Elbow	Up to 3 auxiliary sound indicators	1 auxiliary sound indicator (torso only)
	Supination	1 visual indicator	NA
	Task completion	1 audio indicator for all tasks	1 specialized audio indicator (only for lift task)
Terminal	Hand trajectory	Visual summary	Visual summary
Summary	Spatial classifier	NA	1 visual summary
	Temporal classifier	NA	1 audio summary
	Spatiotemporal efficiency classifier	NA	Audiovisual summary

The HAMRR system offers a reduced number of the real-time feedback components (specifically in terms of number of joint function aspects tracked) in comparison to the AMRR system given the lack of supervision and adaptation. While the *number* of streams is reduced,

participants accepted the HAMRR system's use of more *distributed* feedback provided on the table, on the screen, and less frequently, with an iPad.

As discussed in the conclusion of Chapter 3, training with either AMRR environment led to improvement in the functional assessment of untrained tasks as measured by the Wolf Motor Function test, which is suggestive of the generalizable value of training with respect to functional tasks. The use of abstract feedback focused on the underlying aspects of movement within a variety of tasks, and applied within a digital-physical environment, is intended to contribute to generalizable learning. However the extent to which the design of the feedback is responsible for such gains is unknown, given that the control group of the clinical AMRR study also experienced significant improvement in functional outcomes. The collective results of the AMRR system have demonstrated that interactive training with abstract feedback does not hinder functional gains in supervised therapy and can be used to achieve functional gains in unsupervised training. Additionally, compared to supervised traditional therapy, the greatest added value of interactive training with abstract feedback is in its ability to stylize movement quality. While the extent to which movement quality improvements are necessary to achieve the most effective neurorehabilitation therapy (e.g. for sustaining functional gains) is still under investigation, movement quality improvements resulting from the use of both systems (to a greater extent in the clinical than in home-based training) have not hindered functional gains. The ability of abstract, assistive feedback to move the value of features in a particular direction that is encoded in the feedback design is supportive of the application of interdisciplinary design principles within INR contexts. Further exploration into the relationship between movement quality and feedback exposure are discussed next.

7.2 Stylizing Movement Quality Using Abstract, Assistive Feedback in a Highly Adaptive Context

Evidence collected by both the clinical and home-based AMRR systems supports that movement features can be stylized using abstract assistive feedback; the extent to which stylization can be achieved is likely a function of both initial impairment and adaptation of training,

given that either existing impairment or increased sensitivity to the feedback can trigger feedback encoded with the direction for improvement. The amount, type and sensitivity of feedback required are dependent upon the participant's needs.

The following discussion is the result of collaboration between former MRR team member Yinpeng Chen and the author to explore both the aggregate and instantaneous effects of exposure to assistive feedback. For 3 participants who completed training with the clinical AMRR system, the overall exposure to feedback over the duration of one month of training is shown with resultant improvement across multiple aspects of movement. Then the results of an exploratory method for measuring local effects on performance following exposure to explicit assistive feedback in the clinical AMRR system are presented.

7.2.1 Clinical AMRR evidence: 3 participant profiles demonstrate that customized exposure to feedback yields improvement in several movement features. Highly adaptive feedback used in a nonlinear manner can lead to consistent kinematic improvement across participants of various deficits, as was demonstrated by the study evaluating use of the clinical AMRR system during supervised training with a therapist present to adapt the system and feedback. Table 22 lists the ranked movement aspects (in order of training priority) of each participant's impairment profile and resultant feedback dosage of three participants who received clinical AMRR therapy. Based on the pre-training evaluation, a unique impairment training profile was determined by the physical therapist and attending physician for each participant. For each set during training, the clinician determined the movement focus and selected the appropriate feedback components and sensitivity to use. Table 22 illustrates 3 examples of customized training achieved by providing the therapist (the coach) with access to media tools that can be enabled/disabled and varied in sensitivity. The corresponding distributions of resultant focused training on relevant movement aspects are presented as percentages of total sets completed within the 4-week training period. Figure 31 presents the average changes in kinematic performance for various movement aspects, measured prior to and immediately following AMRR training. Measurements are taken from a set of ten reach to grasp movements to an elevated

cone located at the participant's midline, unassisted by feedback. Pre and post kinematic performance were analyzed using the Wilcoxon rank-sum Test due to the small sample number of reaches. Movement aspects that received training focus are indicated.

Table 22 and Figure 31 demonstrate that customized approaches to training using assistive feedback can result in kinematic improvements for participants of different impairment. Though each participant experienced training with different distributions of feedback exposure, each participant improved across almost all of their respective focus areas. The exceptions are Participants 1 and 3 who did not improve in horizontal trajectory, which may be related to more attention given to accuracy with respect to the target's elevation, and Participant 1 who did not increase in speed, but remained within close range of 0.5 m/s. All participants improved in multiple aspects of movement not designated as focus areas as well, suggesting the value of training with feedback designed to reflect the interrelationship of movement components.

Table 22
Training distributions of 3 participants from the AMRR clinical study

		Ranked Movement Aspects of Impairment Profile	Related Movement Features	% focused trainir
	Participant 1	1. Torso and shoulder compensation	Shoulder compensation	35.09
Rated Impairment	Mild	2. Inconsistenty of elbow extension	Peak speed	15.00
Age	76	3. Insufficient elbow extension	Torso compensation	12.57
Mo. post-stroke	6	4. Trajectory	Targeting	9.65
Sex	F	5. Joint Synchrony	Others	9.52
Lesion	left basal ganglia & periventricular white matter infarct		Elbow extension	9.11
			Trajectory	9.06
	Participant 2	1. Insufficient elbow extension	Torso compensation	28.9
Rated Impairment	Mild to moderate	2. Insufficient shoulder flexion	Elbow extension	23.2
Age	74	3. Insufficient speed	Others	20.2
Mo. post-stroke	7	4. Slow initiation of movement	Trajectory	12.5
Sex	M	5. Torso compensation	Peak speed	8.1
Lesion	left-sided middle cerebral artery infarct		Velocity bellness	7.1
	Participant 3	1. Insufficient elbow extension	Torso compensation	21.5
Rated Impairment	Moderate	2. Insufficient shoulder range of motion	Others	20.6
Age	66	3. Shoulder and torso compensation	Trajectory	19.1
Mo. post-stroke	6	4. Ataxia	Elbow extension	18.2
Sex	M	5. Targeting	Velocity bellness	12.7
Lesion	multifocal embolic left hemiparetic cerebral infarctions		Joint correlation	7.9

An example of training using feedback on correlated aspects of movement can be seen in participants 2 and 3, who each began training with insufficient elbow extension as his top-ranked movement impairment and experienced the most focused training in torso compensation.

This example illustrates how a more direct mapping encouraging explicit information processing on torso compensation was also utilized to promote elbow extension. Multiple types of feedback (e.g. feedback encouraging explicit versus implicit processes) catered in design to communicate performance of specific aspects of movement (trajectory versus joint relationships) can allow for both targeted and integrated training of multiple movement aspects. For example, in Participant 2's training, feedback on trajectory and speed were utilized to train individual performance aspects with resulting improvements, or were utilized in parallel to focus on training velocity bellness, also resulting in improvement. Improvement in joint correlation also utilized the integration of individual intermittent mappings in the context of continuous streams of activity level feedback in all 3 participants, for example, to improve performance of both individual joint function and integrated joint correlation.

Training also accommodated focus on activity level versus body function level movement aspects. Participant 1, rated with mild impairment, was able to maintain the majority of her activity level performance while improving all of her body level aspects that related to focused training. While over half of Participant 2's training focused in torso compensation and elbow extension, he experienced significant improvements across most features presented in both body function and activity level training. Participant 2's significant worsening in shoulder compensation could potentially be addressed with longer treatment periods allowing for focused training on this parameter.

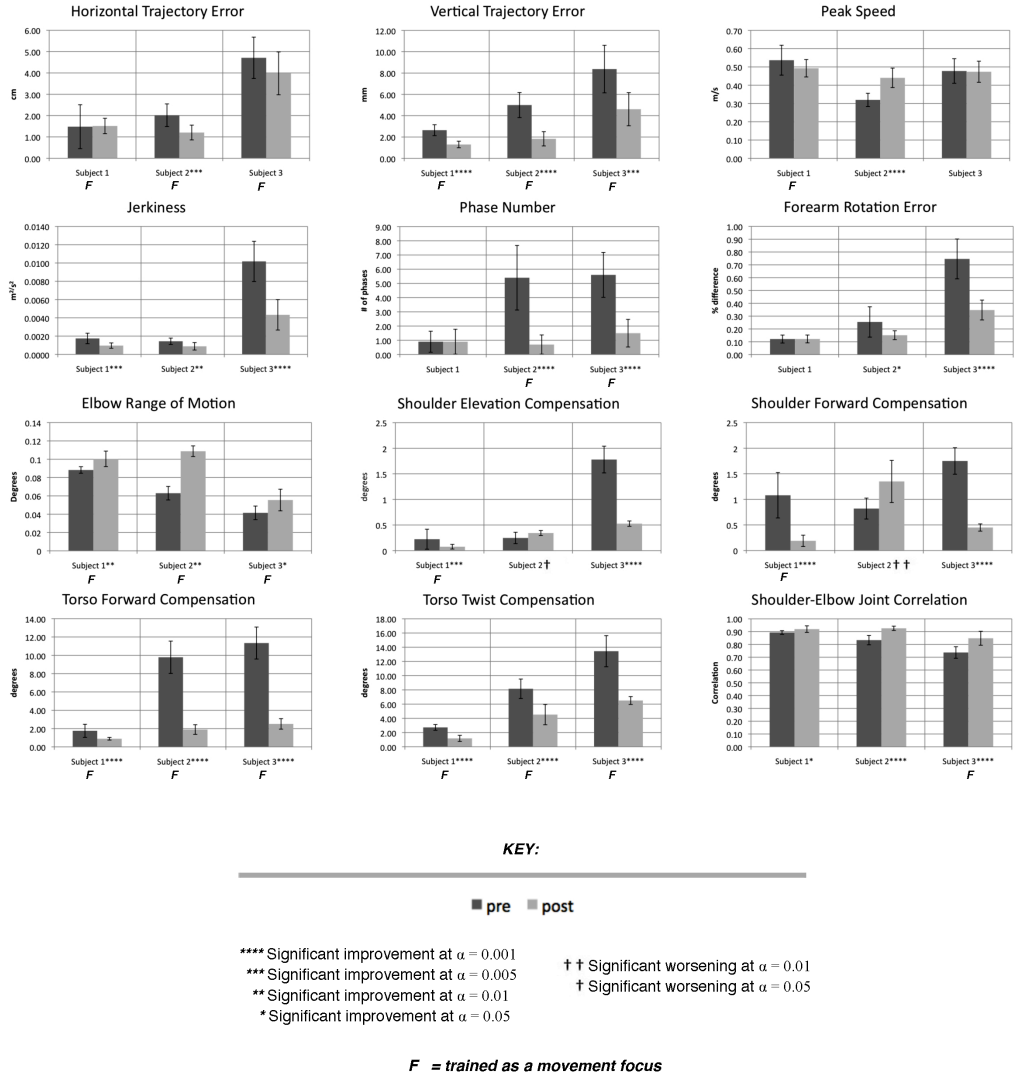


Figure 31. Average changes in kinematic parameters measured prior to and following 12 sessions of training with the clinical AMRR system. Raw mean values are presented for the unsupported (6-inches above the table surface) cone target located at the participant's midline, one of four target locations evaluated during the pre and post evaluation sessions.

7.2.2 Clinical AMRR evidence: exploring local changes in performance following exposure to explicit assistive feedback during training. The following method was developed to better gauge the added value of AMRR feedback to rehabilitation training on the level of individual reaches (*trials*). Individual trials are compared in sequential pairs to evaluate the correlation between observable feedback in one trial and improved performance of kinematic

variables in the trial immediately following. Percentage improvement in performance of a specific kinematic variable after the presence of feedback was calculated as follows:

1. A trial *k* was selected if performance of a kinematic variable *deviated* beyond a threshold determined from movement references measured from unimpaired individuals.
2. Within these selected trials, if error feedback was triggered, the trial *k* was classified as *with feedback* (FB). If the error feedback was not triggered (due to low feedback sensitivity) or the feedback component was turned off for that trial, the trial *k* was classified as *no feedback* (NFB).
3. For the two resulting sets of FB and NFB trials, the mean performance of all initial trials *k* ($p_{k\ mean}$) was compared to the mean performance of all immediately following trials *k+1* ($p_{k+1\ mean}$) by calculating the percentage change:

   $$\%\ change_{\ within\ FB\ set} = 100 * (p_{k+1\ mean,\ FB\ set} - p_{k\ mean,\ FB\ set}) / p_{k\ mean,\ FB\ set}$$

   $$\%\ change_{\ within\ NFB\ set} = 100 * (p_{k+1\ mean,\ NFB\ set} - p_{k\ mean,\ NFB\ set}) / p_{k\ mean,\ NFB\ set}$$

4. The difference in percentage improvement between the NFB and FB sets of trials was calculated:

   $$difference\ in\ \%\ improvement_{\ FB\ -\ NFB} = \%\ change_{\ within\ FB\ set} - \%\ change_{\ within\ NFB\ set}.$$

Table 23 lists the difference in percentage improvement between adjacent reaches when explicit assistive feedback was present versus when feedback was not. Trajectory error, shoulder compensation, torso compensation, and supination error each are mapped to concurrent feedback that is designed for explicit awareness of performance. Thus error feedback on these attributes can be utilized immediately by the participant to correct movement performance in a subsequent trial. Bolded values in Table 23 indicate percentages of improvement for a kinematic parameter given its corresponding feedback mapping. For most of the variables listed, kinematic performance improved more (indicated by the positive percentage listed) following erroneous trials that triggered its corresponding feedback, as compared to following trials that did not have this feedback mapping expressed. For all 3 participants, for example, forearm rotation error

improved by more in trials that followed the triggering of the feedback mapping for forearm rotation error (i.e. image rotation) as compared to following trials with error in forearm rotation that did not trigger the feedback. Similar patterns of improvement can be seen for all 3 participants for vertical trajectory error and torso compensation, indicated by the bolded positive percentage improvement values.

Table 23 also lists the difference in % improvement for feedback versus no feedback trials in the performance of a given kinematic variable following the triggering of feedback mapped to *different* kinematic variables (non-bolded percentages). For example, for all 3 participants, torso forward compensation improved more after trials that triggered feedback on horizontal or vertical trajectory error (i.e. horizontal or vertical image stretching) than after trials that had significant torso compensation error but did not trigger image stretching.

Results presented in Table 23 reveal indices that concurrent AMRR feedback designed for explicit understanding on performance of a given kinematic variable can lead to immediate self-assessment and increased correction for that targeted aspect of movement. Furthermore, the correlation between increased improvements in a kinematic parameter and the presence of feedback mapped to *different* kinematic parameters may suggest that AMRR feedback promotes integrated training; it can allow the user to derive relationships between different aspects of movement through an extraction process (i.e. gain understanding after longer term experience with multiple feedback components), such as the effect of proximal body movements on distal end-point activity. Differences among the participants' performance improvements in relation to the triggered feedback demonstrates that the effectiveness of each feedback mapping can vary by user, providing support that an adaptable feedback paradigm catering to the needs of each participant is necessary. For example, participant 1 appears to respond better to feedback on vertical trajectory (vertical image stretching), which may have shifted her focus away from self-correcting concurrent horizontal trajectory performance.

A limitation of this method is that effects of feedback mappings are considered independently, when in fact improvement is likely the integration of multiple feedback

components. Future work should include analysis of relationships between other feedback mappings that encourage more implicit processes (e.g. elbow extension, joint correlation, velocity profile) and correlated performance improvements. These aspects of movement, which require longer experience with the system, must in turn be assessed across multiple trials or sessions.

Table 23
Difference in % improvement for explicit FB versus the NFB trials for kinematic variables reflecting trajectory, forearm rotation, shoulder and torso compensation.

		Horizontal Trajectory Error *Feedback*	Vertical Trajectory Error *Feedback*	Forearm Rotation Error *Feedback*	Shoulder Compensation *Feedback*	Torso Compensation *Feedback*
Participant 1	Horizontal Trajectory Error	**-7.7%**	-16.0%	-22.7%	7.1%	8.4%
	Vertical Trajectory Error	52.5%	**52.5%**	43.5%	47.4%	36.2%
	Forearm Rotation Error	22.4%	38.4%	**7.1%**	2.0%	44.2%
	Shoulder Elevation Compensation	-3.2%	20.7%	-5.9%	**-4.0%**	19.6%
	Shoulder Forward Compensation	13.9%	21.4%	0.8%	**9.1%**	31.5%
	Torso Forward Compensation	37.7%	33.6%	23.7%	-3216.0%	**39.2%**
	Torso Twist Compensation	18.7%	26.7%	-31.1%	2.3%	**30.3%**
Participant 2	Horizontal Trajectory Error	**10.3%**	4.8%	38.6%	24.0%	2.3%
	Vertical Trajectory Error	24.8%	**29.0%**	22.5%	-11.5%	38.0%
	Forearm Rotation Error	9.0%	25.7%	**36.4%**	23.3%	-9.3%
	Shoulder Elevation Compensation	-2.3%	-2.0%	-5.3%	**20.6%**	-8.8%
	Shoulder Forward Compensation	5.9%	3.5%	-4.7%	**-5.2%**	5.9%
	Torso Forward Compensation	19.1%	12.1%	11.2%	6.5%	**25.3%**
	Torso Twist Compensation	11.8%	27.5%	3.6%	26.3%	**16.9%**
Participant 3	Horizontal Trajectory Error	**13.0%**	1.3%	-3.1%	-184.0%	2.2%
	Vertical Trajectory Error	2.5%	**22.1%**	-23.8%	17.8%	11.1%
	Forearm Rotation Error	-0.2%	0.1%	**31.0%**	5.9%	-1.8%
	Shoulder Elevation Compensation	4.1%	2.1%	5.8%	**0.9%**	0.8%
	Shoulder Forward Compensation	0.1%	0.8%	0.6%	**27.5%**	-2.2%
	Torso Forward Compensation	33.7%	27.1%	27.6%	60.2%	**36.2%**
	Torso Twist Compensation	16.4%	6.0%	12.7%	-1.8%	**12.6%**

7.3 Exploring Changes in Performance Given a Fixed Dosage of Mixed Feedback: Challenges and Considerations

The home-based AMRR system facilitates an aggregate experience that leads to functional improvement but does not train movement quality to the extent of clinical AMRR. The clinical AMRR study's outcomes were well fitted to the training, in that detailed feedback was provided on multiple aspects of movement performance that were also used as outcome measures. The design of the home system takes a different approach, given our hypothesis that the media experience should facilitate an overall narrative rather than exclusively focus on stylizing movement quality. As a result, the dosage of training focused on stylization of movement is decreased over time, as more exploratory training measures were increased (e.g. providing high level feedback based on movement classifiers).

In HAMRR training, participants were exposed to 1 of 3 fixed training paths (protocols). Paths varied primarily by the amount of off-table and transport training, but were similar in terms of distribution of feedback and training foci. Given that participants were exposed to a similar dosage of feedback, performance over time was compared across participants to determine if any commonalities or differences arise, and to explore potential considerations that are important for re-design. The following sections discuss change in performance across spatial features over time given its feedback comprises the more explicit mappings (which can have a local effect).

Figure 32(a) plots the relative amounts of training with respect to feedback pertaining to spatial accuracy as the percentage of total sets trained per day in Levels 1, 2, and 3. After the first week of supervised training, dosage is summed across days completed *between* training monitoring sessions, when performance is sampled. Figure 32(a) demonstrates that over the course of 15 sessions, the percentage of sets with Level 1 spatial training is reduced, as Level 2 spatial training and Level 3 overall efficiency training are increased.

Figure 32(b-d) plots the average vertical trajectory error over time for the reach to grasp cone task measured at the pre-test (time point 0), Training Monitoring (TM) sessions 1-4 (time points 6, 9, 12,15) and post-test (time point 16). Moderately impaired subjects 7 and 8 experience

the greatest changes in performance after the first two weeks of training during which, relative to other weeks, the highest amount of low-level training is completed. Once performance by subjects 7 and 8 dips below the threshold of triggering feedback, performance error appears to increase. Mild participants 1,2, and 3 shown in panel (d) began training below the threshold of triggering feedback. As training progressed, average error still decreased for all four subjects, but began to either plateau or increase as higher-level training increased. Mild subjects 4 and 5 shown in panel (c) follow patterns of fluctuating performance. Though not shown here, similar patterns can be seen in horizontal error; in several cases subjects who are initially under the feedback threshold remain there, while those who go over the average then begin to drop down in the following week.

Subjects 7 and 8 begin training with higher average vertical error than other subjects, and therefore likely had the most opportunity to trigger feedback for vertical trajectory error during interactive training. Subjects' 7 and 8 less dramatic decrease in error towards the mid-to-end of training may suggest insufficient prior low level training, and/or could suggest that the feedback at higher levels (which increased in relative dosage as training progressed) did not adequately reinforce trajectory training at the low level. For example, the visual feedback for curvature in Level 2, which was increased after the first 2 weeks of training, does not explicitly differentiate between horizontal and vertical errors. In the case of mild Subjects shown in panel (d), the initial decrease after the first 2 weeks of training could be the result of integrative training, given that several other parameters for Subjects 1,2, and 6 improved and could have influenced trajectory accuracy. This fluctuation of values for the highest functioning Subjects 4 and 5 could be attributed to an initial lack of exposure to low-level feedback, given that feedback was likely infrequently triggered by these participants for the first 2 weeks of training, coupled to lack of consistent change across other parameters, given that several features for these participants do not improve.

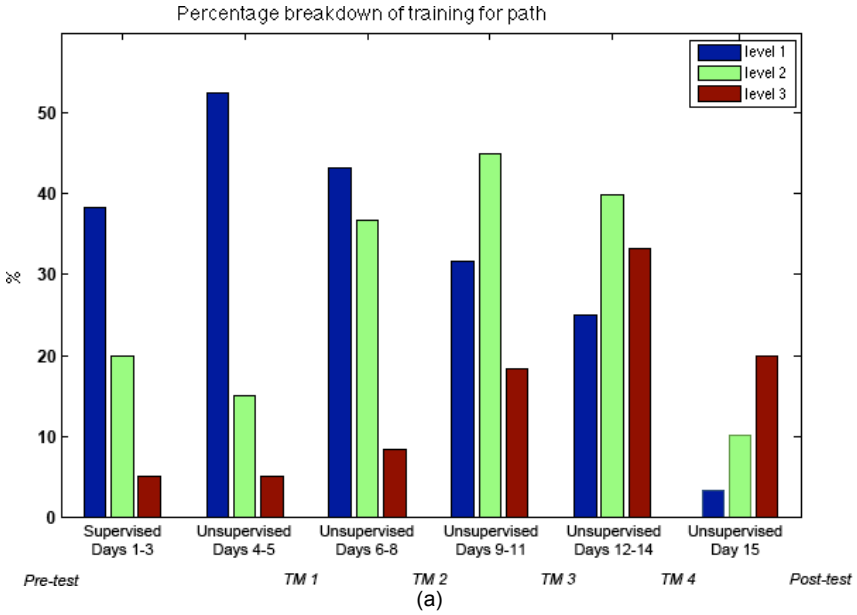
Figure 33 plots the average path ratio over time measured during the four training monitoring sessions for the transport up and transport down tasks. Subjects 7 and 8, shown in

panels (a-b) are missing several samples but are included for the sake of completeness. Subject 6 shown in panels (c-d) achieves the most improvement across the four training monitoring sessions, reaching the non-impaired range before the last session of training. The other Mild Subjects 1 and 2 begin within non-impaired ranges but by the end of training do slightly improve and move somewhat closer to Subject 6's performance by the end of training. Subjects 3, 4, and 5, shown in panels (e-f) remain about the same in their performance, with Subjects 4 and 5 exhibiting similar behavior as they did in vertical trajectory error.

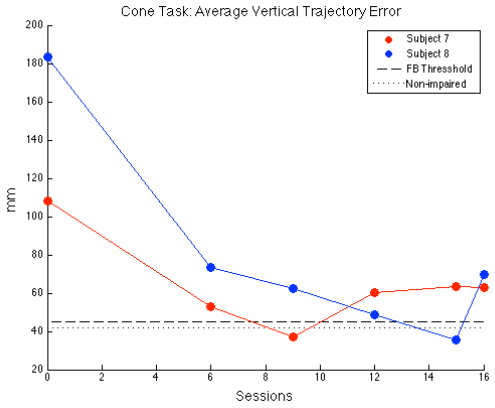
There was no independent threshold for path ratio alone that triggered feedback due to the fact that the overall efficiency measure combined path ratio, speed phases and total reach time. Thus negative or positive feedback received in Level 3 could be a response to poor or excellent performance in any or all three of these areas (e.g. one feature could overshadow the others or all features be fairly similar in value). It is currently unclear if the slight convergence of performance for Subjects 1, 2 and 6 reflect any similarities in training effects but more intensive training or an adjustable component approach to Level 3 training (e.g. weighting components that the participant struggles with most) may have resulted in greater improvements across subjects.

Currently the multi-leveled design in the home-based AMRR system to some extent relies upon being able to trigger feedback in Level 1 to establish meaningful interaction with higher levels of feedback. While there is correlation among exposure to different levels of feedback given they each pertain to trajectory accuracy, lack of exposure to error feedback in lower levels (e.g. Level 1) does not necessarily mean there will not be exposure to error feedback in Level 2 or 3. Level 2, and to a greater extent Level 3, are designed to promote a "searching for solutions" by the participant in order to facilitate independent learning; yet without sufficient exposure to negative feedback in Level 1 (combined with exposure to higher levels), at best we cannot be sure that there was enough time for a meaningful internal model to be formed that forms a relationship between lower and higher level feedback. This is perhaps evident in the fluctuations in performance for Subjects 4 and 5 given lack of exposure to Level 1 negative feedback. This is not to say participants cannot to some degree benefit from feedback provided by higher levels

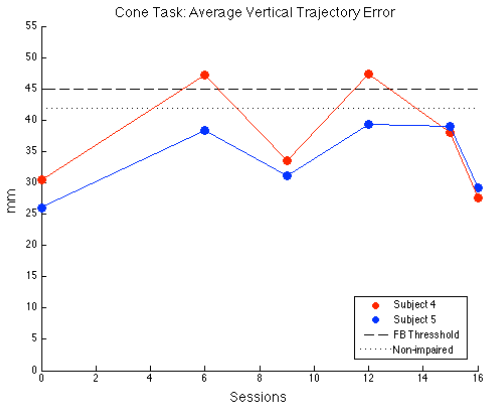
alone; these levels do both indicate the magnitude of error and in Level 2, a specification of which feature domain is being evaluated (e.g. spatial performance versus temporal performance). However, in order to maximize the effect of training, future approaches to utilizing multilevel feedback for unsupervised training should potentially consider how various levels of exposure to error feedback across levels can affect the feedback design's cumulative impact.



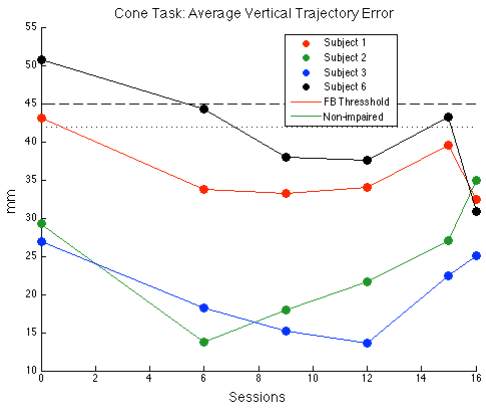
(a)



(b)



(c)



(d)

Figure 32.Percentage of sets training spatial accuracy across Levels 1, 2, and 3 versus performance of vertical trajectory error over time. Participants are grouped by relative impairment level.

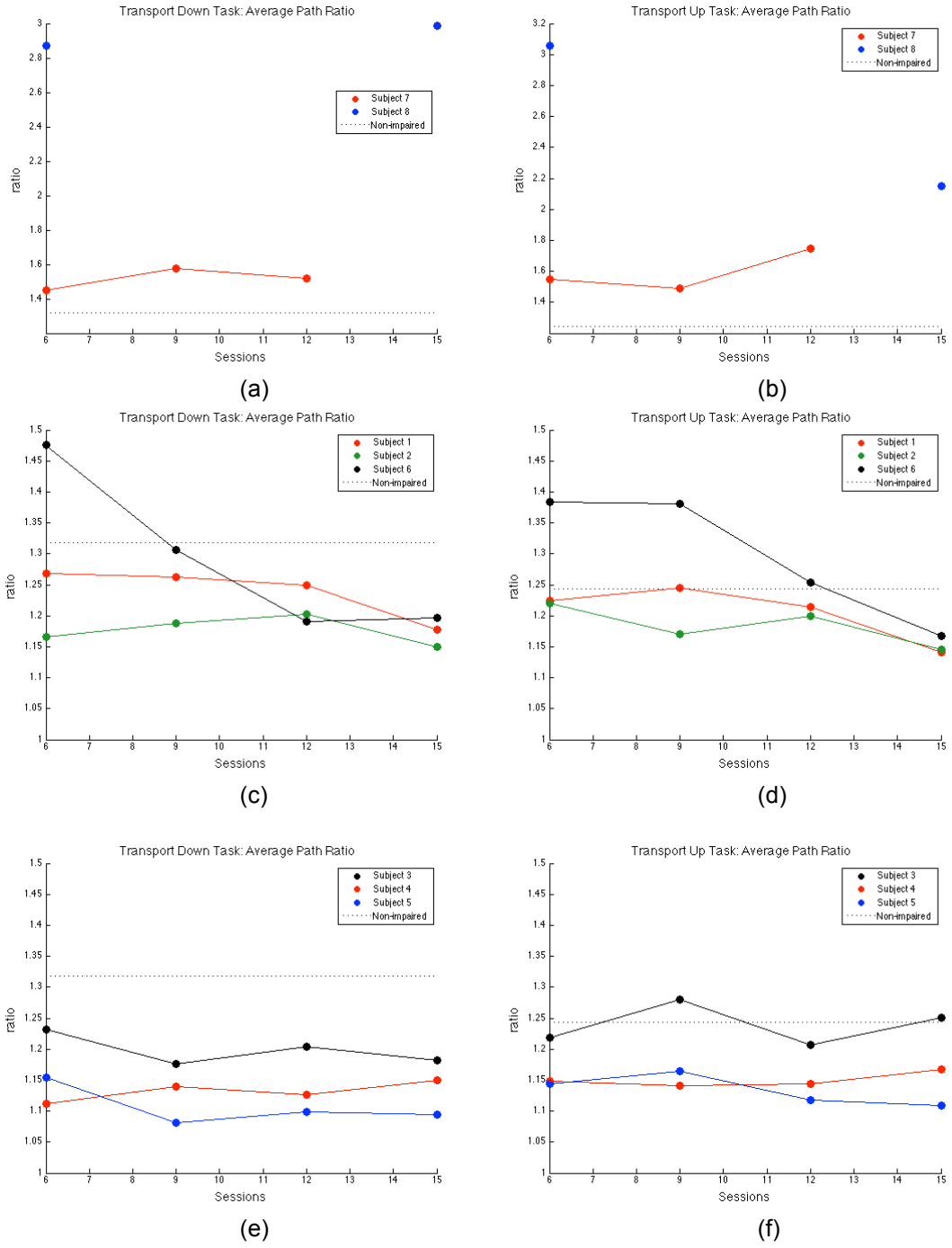


Figure 33. Path ratio performance for the transport up and transport down tasks measured on training monitoring days only. Participants are grouped by relative impairment level.

7.4 Challenges in Evaluating Multi-level Design

Results of the study evaluating unsupervised INR training suggest that use of a reductionist hierarchy approach to structuring feedback and interaction scenarios can help maintain engagement, induce integrated active learning of movement components and related complex tasks, and consequently, increase adherence and impact of unsupervised INR. As an aggregate effect, significant improvement was achieved in both clinical functional and motor ability scales. Since related methods have been successfully applied in other domains (e.g. arts practice, interactive learning discussed in Chapter 2) it is likely worth pursuing further investigation of such an approach to determine how to maximize gains within INR.

A key challenge in evaluating multilevel feedback for unsupervised INR is that aspects of one or several axes (time delivery, meaning, task complexity) could require redesign. For example, while the meaning of the Level 2 visual feedback (a linchpin between lower and higher level training) was successfully tested in a user study with non-impaired participants, such results cannot guarantee successful implementation with stroke survivors. Although there are indices that unsupervised training could benefit from a multi-level approach, the required amount of therapist intervention, low-level training, or re-design of higher level feedback requires further investigation using a system with greater adaptive capabilities in terms of overall training path composition: task type, sequence, dosage and corresponding feedback sensitivity.

Furthermore the features used to assess and drive feedback for complex tasks may not be the best-suited features for training. More investigation into the assessment complex tasks, such as potentially using statistical measures instead of references-based kinematics given the high variance of complex tasks, is required.

7.5 Other Considerations for Re-Design based on Observations of Participant Interaction with the Media During Unsupervised Training

7.5.1 Challenges faced by moderate participants in using the visual feedback. While participants overall accepted the use of visual feedback presented in multiple locations (table

versus screen), Subject 7 was observed by the physical therapist “as missing 25% of the visual feedback on the screen after forgetting to look up” following task completion. Future participants, especially those who are moderately impaired and may focus more intently on the physical reaching movement, would likely benefit from an optional audio indicator coupled to the display of the summary visual feedback on screen.

Subject 8 consistently found the visual and audio feedback to be somewhat difficult to understand. When training first began it seemed she was able to see enough to accurately identify the feedback and attempted to correct her movements accordingly for simple visual feedback. However she had visual impairment from diabetic retinopathy and often requested assistance in clarifying content that was on the screen. Across several sessions, subject 8 explained it was “somewhat difficult because I cannot make out all the colors…the screen and colors flashed too quick...couldn't see well due to my visual deficits...Cannot see the detail I need to pick up.” In terms of the audio feedback, the torso sound was easier to understand than the more detailed audio feedback: the “foghorn is too loud but it is shocking enough for me to remember what it means.”...“foghorn, I can understand.”...“reminds me I am out of place.” However “the music takes a lot of concentration away from my movement...(it’s) hard to grasp the concept of which music was the optimum”...“cannot remember what different songs mean.” At times the participant acknowledged that while the music may give “negative feedback” about the slower speed of her movement, she was actually attempting to use a strategy of reaching with elbow instead of trunk flexion. She acknowledged that while this strategy may take her longer to attempt, it is the right strategy to try to re-train normal reaching movements.

The visual feedback should be more readily adjustable depending upon visual acuity. While several aspects of the visual feedback were adjustable at the time of Subject 8’s (time duration on the screen, size of the rock path, removing the water so there is higher contrast with the performance-based elements) these options were not readily available to the therapist when she had to independently administer the study for the two final participants. Such features should be built into an interface for the clinician to facilitate use as needed. Participant 8 also reported

having trouble deciphering finer aspects of the audio feedback. While interpretation of audio feedback often requires more time and experience than visual feedback, an option to replay music as needed could potentially facilitate the process and the participant's understanding.

While Participant 8 experienced difficulty in reliably perceiving the feedback she did demonstrate the ability to decode multistream visual scenes. She expressed that she would have liked for the Level 3 scene to communicate multiple aspects of her movement individually, such as "lightening being connected to one part of her movement, and waves being connected to another". Perhaps this request was a side effect of her inability to use the visuals associated with low-level training given its finer detail, whereas the Level 3 feedback used bolder visual features that were more easily perceived. Future considerations might include using feedback with more coarse visuals to communicate multiple aspects of performance for those who have trouble deciphering smaller details. Regardless of the motivation, Subject 8's request does further support acceptance of multistream media, despite even having visual perceptual challenges.

7.5.2 Increasing both challenge and reward system. Overall participants reported a lack of challenge using the home-based AMRR system. Adaptive training that increases the sensitivity levels and varies types of tasks based on participant need would certainly help address this problem. However, the repetitive nature of the experience is also likely due the fact that higher functioning participants often triggered efficient feedback that was always the same.

Because the feedback is designed to parallel the form of the movement assessment (concept of form coherence), variations in error along a continuum were emphasized to communicate magnitude and direction of error, while the efficient spectrum was left as a discrete zone (similar to how kinematic impairment is considered). As a result, most of the variation and visual interest was provided in the form of *negative* feedback. After watching participants of mild impairment use the system for a month in the clinic, the lack of narrative for cumulative reward became especially apparent, as several participants reached the 'feedback ceiling' of efficient performance early on in training. While variation within the non-impaired zone is not important to emphasize for INR contexts, the sustained presence of remaining within the non-impaired

performance would likely be beneficial to participants over long-term training. In other words, participants should likely be rewarded for consistency in a more explicit manner than is currently implemented. Re-design of the feedback should thus consider a means to augment positive feedback over time to better communicate the overall narrative of performance and further incentivize long-term training.

7.5.3 Redundancy and specificity of instructional content. Instruction was provided before each task on a given training day. A full-detail instruction was provided if the participant were performing the task for the first time, otherwise summarized content was used if the tasks appeared again that day. While successful in guiding participants to setup and conduct therapy independently, several felt that the instructional media was too repetitive. Participants were observed sometimes dozing off or ignoring the instructions, as they would perform the incorrect task following the conclusion of the instruction. While this happened infrequently, excessive use of instruction should be avoided. A potential undesirable side effect would be for the participant to also begin to ignore the screen-based feedback as well.

Some participants also felt that the instructional media was not literal enough. For example, sometimes a video displayed a task requiring a reach to an object that was not in the same location of the object on the table. While most participants were able to generalize the instruction to their individual setup, some occasionally reported being confused by the mismatch. Such feedback from participants supports the concept that prescriptive direct representational media can be distracting if it deviates from the activity being performed by the participant. Thus redesign should potentially consider instructional videos that leave less room for interpretation and are closer to duplicating the exact location and type of task being asked of the participant.

7.5.4 Sampling during training and facilitating dialogue on the feedback. Utilization of the feedback by the patient is difficult to measure. While the appropriate way to evaluate the use of feedback relies on multiple sources of measurement (e.g. questionnaires, changes in performance, and active discussion with patient) the most appropriate sources and combination of these measurements is unknown. Preliminary evidence from the clinical AMRR study

(described above) revealed strong correlations between improved performance and the preceding presence of relevant feedback, but did not account for how the effect changed over time or the cross-effects that may result from using multiple feedback components concurrently. To more frequently sample how the patient interacts with the system during unsupervised training, the home-based AMRR protocol included a weekly intervention by the therapist to administer a questionnaire on the ease of use of the system's interface and media feedback. While the questionnaire results indicate that all patients found the system interface and feedback easy to understand and use, the self-reporting cannot determine if the patient is actually using the feedback to help understand and improve performance during training.

To complement prior work in developing methods to evaluate the efficacy of the feedback, future extensions of home-based AMRR should utilize interactive probes (periodic questions by the system on how the patient is understanding the feedback) into existing instructional content to better evaluate feedback utilization during training. Interactive probes can take the form of dialogue screens immediately following completion of a single or set of reaches, in which the system asks the patient to predict the feedback he will experience before it is displayed. By measuring the accuracy of the patient's prediction immediately after he completes a movement, the use of interactive probes can potentially reduce the effect of confounding variables produced by inaccurate recall over time and by asking patients questions about the feedback out of context instead of "mid-experience." Such a means for evaluation could also be used to observe if memory of higher-level elements were extracted correctly (e.g. color as an indication of magnitude used in Level 2).

Periodic discussion with the therapist was received well by participants, especially by those participants who were higher level in function and could receive feedback on aspects of performance not measured by the system. However in the future such interactions should better address the use of feedback as a medium for discussion (e.g. have the participant explain what they see and why they think they saw it). Future design should enable participants to flag individual trials or sets using the system dialog buttons so that s/he can then discuss any issues

with the therapist at a later date. Such a flagging system would bookmark the data, video and feedback provided by the system so the therapist can have a basis with which to discuss the participant's source of confusion or perhaps adjust sensitivity in the system in a more informed manner. Similarly a reminder system could also potentially help participants verbally annotate and record sources of confusion following sessions. Participants often left sessions without having the opportunity to ask questions (often by design given we wanted to facilitate independent training). A prompt to make an audio or video annotation (using an iPad app for example) immediately after training was completed could help ensure these issues were not forgotten for when the participant does have a meeting the therapist at a later date.

CHAPTER 8

FUTURE DIRECTIONS

8.1 Considerations for designing appropriate media content

When designing media for stroke, for the most part, one is targeting a mature audience. Care should be taken to avoid designing feedback that is perceived as patronizing. While the clinical AMRR system focused on purely formal elements of an abstract experience, the home system ventured into metaphorical content and story telling. While the concept of traveling on a boat is by no means the optimal, singular solution, the intent was to use neutral content that was appealing yet relatable to a broad audience as a means to explore if semantics can be used to connect multiple levels of unsupervised learning. More work is needed to evaluate other types of content (metaphors) to suit the needs of different participants.

Representation of activities that are important to the participant should be used with caution. The concept of recovery and participation in daily life is highly sensitive and can affect participants differently. While some participants are motivated by trying to return to skilled activities they performed for enjoyment or as an occupation before stroke, for others, these topics are potential sources of frustration and sadness. For example, the clinical AMRR system allowed for customization of the image that broke into particles. One stroke survivor who opted to use personal pictures of his fishing trips ultimately was distracted and upset by them, conceding that he would never be able to participate in fishing the same way he did before. He requested they be replaced with the default system images (paintings and iconic images). Similar observations were made with a participant from the home-based AMRR study, who conducted his own practice as a dentist. While he continued to contribute to the practice in other ways, he expressed disappointment in being unable to return as a practicing dentist. In contrast to these two participants, another stroke survivor who participated in a pilot study evaluating the usability of the home system expressed that being a musician has motivated him to *want* to get better. As a result he would set personal goals to use his drum-set and drum at a particular rate, comparing his affected arm to his less affected arm as a baseline. He expressed pleasure in knowing how

far he had come and looked forward to achieving more gains in the future. While level of impairment is a strong factor among these examples (the first participant mentioned was severely impaired, while the latter two were mild) discussions with these participants support that participants are likely motivated differently, and should be involved in the design process for long-term compliance.

8.2 Participant-defined benchmarks to involve the participant as active creator

The first aim of testing clinical AMRR was to determine if media that utilizes interdisciplinary design concepts, well supported across other multiple disciplines, could be successfully applied for INR. While overall compliance and successful application have been observed for the short term (span of one month training), sustaining long-term participation among stroke survivors will likely have the greatest impact on recovery. To motivate long-term compliance, ultimately stroke survivors need to become active participants in selecting and achieving goals, especially as attention shifts to activities of daily living performed in highly variable environments without supervision. Furthermore, the concept of recovery among stroke survivors is highly contextual and dependent upon a number of factors (Sumathipala, Radcliffe, Sadler, Wolfe & McKevitt, 2011). For example, stroke survivors who live alone face different challenges than those with caregivers. Depending upon such factors the value assigned to different types of activity may also be participant-dependent (e.g. folding laundry versus playing a card game in a social setting). Involving participants in the therapy design progress can potentially help them feel more empowered and engaged with their path to recovery. Customizing training can refer not only to the feedback content, but also defining the activity being practiced by composing a therapy plan. Integrating the use of a metaphor with customized tasks could potentially facilitate a more meaningful experience for the participant. The idea of applying storytelling as feedback could also shift from metaphors in training to participants composing their own narratives of progress by collecting and editing media.

A common theme encountered among stroke survivors who were especially active about their recovery is participant-defined benchmarks. One stroke survivor expressed during a training monitoring session that he was able to reach his affected arm behind his back, while he could not before, which was how he knew he was improving. Another stroke survivor, who served as a short-term consultant on the design of the home system, shared that he would press his hand against a steamed shower window to assess the size of the imprint thus his hand dexterity. While the degree to which these benchmarks can be meaningful might vary (in a functional or motor ability sense), they demonstrate simple activities that are self-motivated and customized to the needs of the patient. INR systems that accommodate participant-defined benchmarks may provide an opportunity for stroke survivors to both capture progress in a more formalized and engaging manner, as well as set other meaningful goals that (with the help of the therapist's approval) also respect the sensitive nature of setting *appropriate* goals. Future directions in media design could facilitate these benchmarks in a variety of ways; however mobile technology provides a particularly effective medium for multimedia self-annotation, tracking, and social sharing with family, caregivers and clinicians.

8.3 Self-tracking and Personalized Care

Applications for portable devices such as smartphones and tablets have tremendous promise for facilitating more accurate personal documentation on daily activity and reflections due to their portability, high quality sensors, and adaptable touch-based interface. Methods for sensing will change (ranging from computer vision to activity-tracking wearable's that may be able to provide more reduced forms of feedback embedded on the device itself). However greatest burden will be on the software interface for incentivizing usage and providing meaningful summaries of activity, as well as providing a means for communication of progress with either the therapist or caregiver, in order to sustain the use of these tools. Mobile devices will therefore likely serve as the primary interface for providing reminders and detailed summaries to the participant. Technology literacy among older adults is also growing. Stroke survivors are

increasingly more accustomed to personal technology given the ubiquity of smart phones, tablets, and wearable's. The popularization of personal tracking in health, fitness and well-being has led to increasing efforts by leaders in mobile technology to create development tools for health and self-tracking, such as Apple's Health-kit's collaboration with Mayo Clinic and Google Fit, which will likely only accelerate innovation and benefit stroke and other mobility limiting disabilities.

8.4 Distributed visual feedback

The home system introduced the presence of visuals in the physical space by providing a light embedded within the targets. The presence of an activated light on a target provided a means for instruction (to which target the participant should reach) and indicated coarse levels of performance using color (magnitude of spatial error). On the other hand, detailed visuals displayed on the screen were designed to gradually reduce dependence on receiving concurrent feedback and promote offline reflection of performance. While this interaction structure intended to guide the participant towards independent reflection, the participant was locked in front of a custom-designed table and screen. Long-term usage in the home will ultimately require systems that are less obtrusive, more mobile, and distributed both in terms of physical location and temporal application.

The use of ambient, long-term displays distributed within the home (in locations meaningful to the participant) could be used in conjunction with a structured training regimen to provide a more ubiquitous means for communicating progress. Portable, networked interactive objects with embedded means for display could also allow for more flexible practice with means for both instruction and communicating levels of performance. The design of different interactive targets with varied visual affordances could facilitate varied types of interaction or target manipulation. Embedding detailed visuals within the interaction space itself (e.g. projection onto the supportive table or touch table with display) was avoided to reduce distraction while performing the movement, avoid forcing an automated pattern of movement, and discourage reliance of feedback in proximal locations in which focus should not be concentrated. However

other ways of applying these means for distributed display could still be highly effective in directing attention to the target and summarizing performance in a portable manner.

8.5 Thinking Beyond to Other Embodied Learning Contexts

In closing the compositional framework is intended to provide a means for designing an experience at multiple entry points to help a participant accomplish a complex learning goal. Not every problem that could potentially benefit from the compositional framework begins in supervised contexts. For the problem of stroke rehabilitation, participants often start their path to recovery in a clinical setting and thus likely benefit from supervised training first. However areas like preventative health care and behavior modification are examples of applications that begin in the wild, or highly uncontrolled contexts. The compositional framework suggests that these areas might benefit from applications that engage individuals in creative activity, where the participant is producing media content as a means to document, understand and potentially communicate his experience with others. Applications for behavior modification are already focused on empowering the individual to change based on the knowledge gained. Thus a unique opportunity exists for applying creative exercises, which are often inherently empowering to expert and layman alike, to such domains as behavioral modification or general activity awareness. Concepts for composing media (such as the interdisciplinary concepts presented in Chapter 4) could potentially serve as a starting point for applying compositional practice for everyday use.

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APPENDIX A

RATING SYSTEM RATIONALE AND RUBRIC

The therapist used the iPad app to capture three types of tasks: a simple task that was trained by the system (reach to grasp a cone at midline), a complex task that was trained by the system (reach to transport a cone or cylinder from an elevated platform to a low platform) and a simple task that was semi-trained by the system (reach to touch an elevated flat surface) – see Figure 1. A rubric for rating movement was developed to provide criteria for the treatment therapists to assess both overall and individual components of movement performance with respect to these tasks.



Figure 1. Three types of tasks captured: grasping a cone, touching an elevated flat target, and transporting a cylinder with/against gravity

Designing the rubric

Rating overall performance. The rubric was designed at Emory University during a training week held for both treatment therapists. A rubric was created so that each task could be assigned a score in terms of the therapist's initial overall impression, trajectory, compensation, hand manipulation, transport (if transport task), release (if transport task), and final overall impression after rating all preceding components. If the final overall impression was different from the initial, then a reason was required. A validated clinical scale (WMFT FAS) was modified to suit the tasks being rated; the resulting criteria that were used to provide an initial overall rating of the participant's performance are listed below. This list of criteria was also used when the therapist was asked to give a final overall impression of performance following assessment of movement components.

Rating individual movement components. The key movement components selected to be rated included trajectory, compensation, hand manipulation (task-dependent), transport (if transport task), and release (if transport task). Criteria for selecting these features included adequate relevance to the range of tasks, visibility to the naked eye, and ability to be assessed from a single camera position. A validated clinical scale for rating the functional contribution of individual movement components with respect to completing a task is currently lacking; therefore movement components needed to be selected and defined in usable terms. Definitions and resulting criteria that were developed are listed below. The rehabilitation experts agreed that a maximum of 4 categories could adequately capture different levels of impairment, whereas any additional categories would be extraneous and could lead to noise across raters. Furthermore the rubric was also designed with discrete decision points in order to reduce the amount of variability within and across raters. Note, for example, a score for compensation is determined by the presence or absence of specific types of movement as opposed to the evaluating the extent to which a movement was present (e.g. degree of compensation).

The following are criteria that defined the rubric for rating both overall performance and individual movement components.

Rate Overall reaching trial (Modified Functional Activity Score from WMFT)

Please rate the trial with a value of 1-5 based on your overall impression of the participant's performance with respect to the following criteria:

1. Cannot complete the task

2. Requires multiple efforts to complete the task within the time allotted

3. Completes the task within the allotted time and with a single effort, but demonstrates at least one of the following:
   - Influenced to some degree by synergy
   - Performed slowly (>50% allotted time) or with apparent effort
   - Performed with the incorrect type of grasp of target object
   - Performed with excessive compensatory movement

4. Completes the task within the allotted time and a single effort. Movement quality is close to unimpaired but may lack
   - Precision
   - Fine coordination
   - Fluidity

5. The quality of movement appears to be similar to that of the rater if he/she performed the task

Trajectory: Accuracy of moving the hand from the start to end position during the reaching phase

1. Does not ever reach the target

2. Demonstrates profound deviation from a direct path during the reaching phase, which may be affected by but is not limited to one or more of the following secondary factors:
   - Synergy
   - Ataxia
   - Spasticity

3. Demonstrates slight deviation (relative to how the rater would perform the task) from a direct path during the reaching phase

4. The trajectory appears to be similar to that of the rater if he/she were

Compensation: Excessive shoulder elevation or abduction and/or torso flexion, rotation, or lateral flexion

1. Demonstrates compensatory shoulder movement with compensatory torso movement in more than one plane

2. Demonstrates compensatory shoulder movement with trunk compensatory movement mainly in one plane

3. Demonstrates noticeable compensatory shoulder or trunk movement

4. The shoulder and trunk are positioned in a manner similar to the rater if he/she were performing the task

Hand Manipulation - *Gross grasp*: Opposition between thumb and fingers about the diameter of the object with the necessary applied force required to lift

1. Does not make physical contact with the target surface

2. Able to achieve a grasp with the wrist initially or ending in prone position

3. Able to achieve a cylindrical grasp with wrist in neutral position, but with effort

4. Cylindrical grasp is achieved in a manner similar to the rater if he/she were performing the grasp

Hand Manipulation – *Touch:* Physical contact with a specified target surface using the finger pads, excluding the thumb

1. Does not make physical contact with the target surface

2. Makes contact with the specified target surface, but does not use finger pads

3. Makes contact with the specified surface using finger pads, and may include
   - Adjusting the finger or hand position prior to making contact
   - Touching other parts of the object besides the specified target surface

4. Touch is achieved in a manner similar to the rater if he/she were performing the task

Transport phase: Translating an object from one location to another while carried by the hand

1. Is not able to lift the object

2. Able to lift vertically but cannot transport laterally

3. Able to transport object but with one or more of the following features:
   - Indirect path from point A to point B
   - Inaccurate or uneven final placement of transported object
   - Accurate and even final placement of transported object yet requires additional effort to achieve final positioning

4. Transport of object is achieved in a manner similar to the rater if he/she were performing the task

Release phase: Extension of fingers and thumb to remove hand from object following deposit

1. Cannot release hand from object

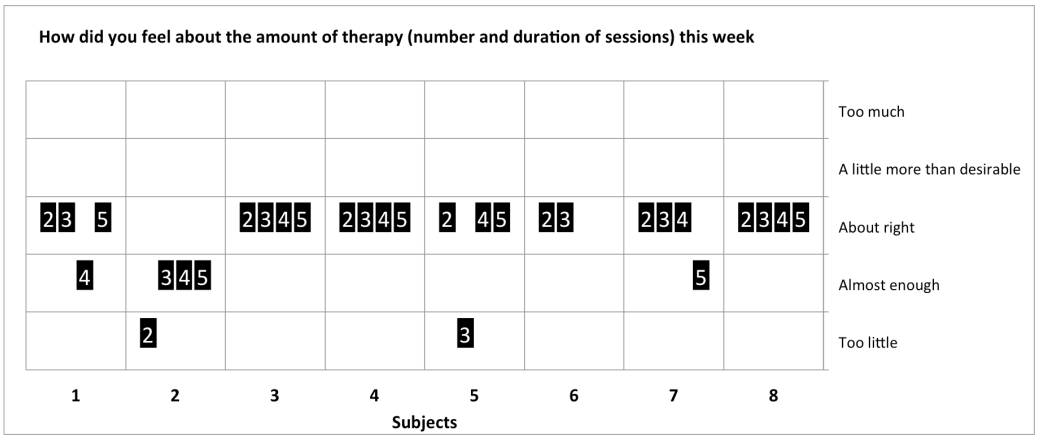
2. Release achieved, but fingers slide along the object's surface

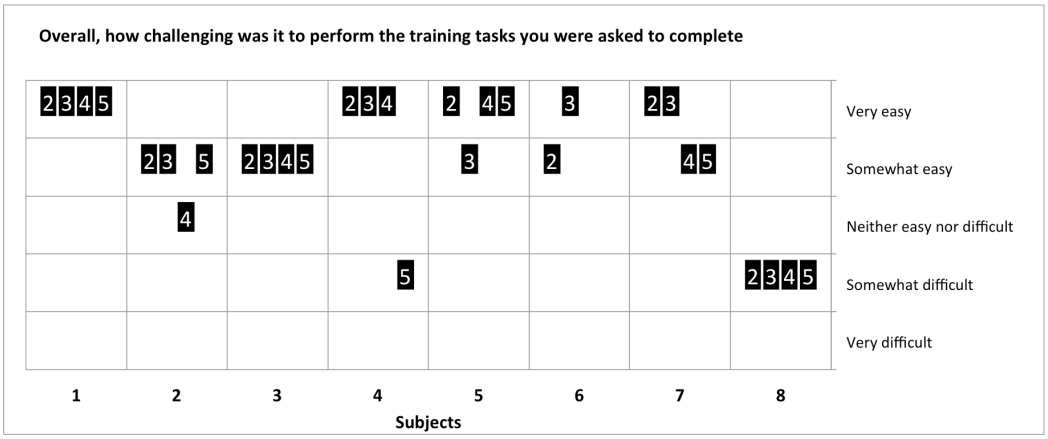
3. Release achieved, but digits release asynchronously

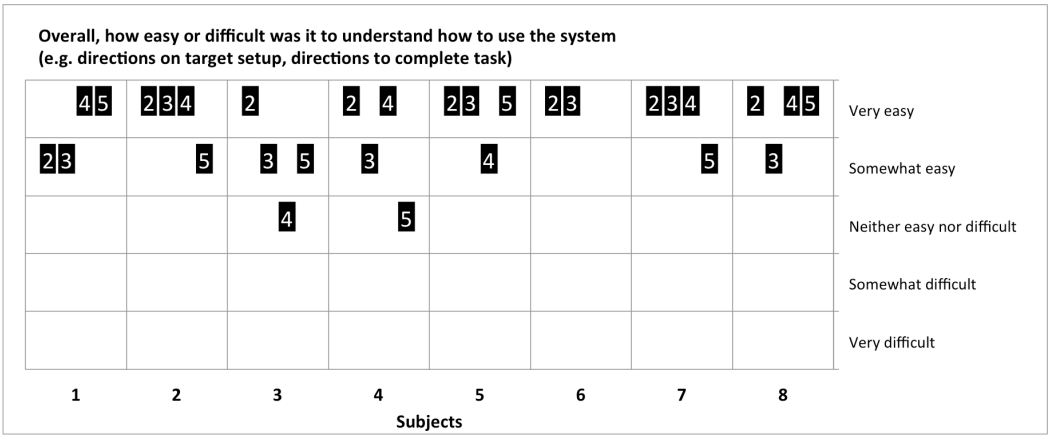
4. Release of object is achieved in a manner similar to the rater if he/she were performing the grasp

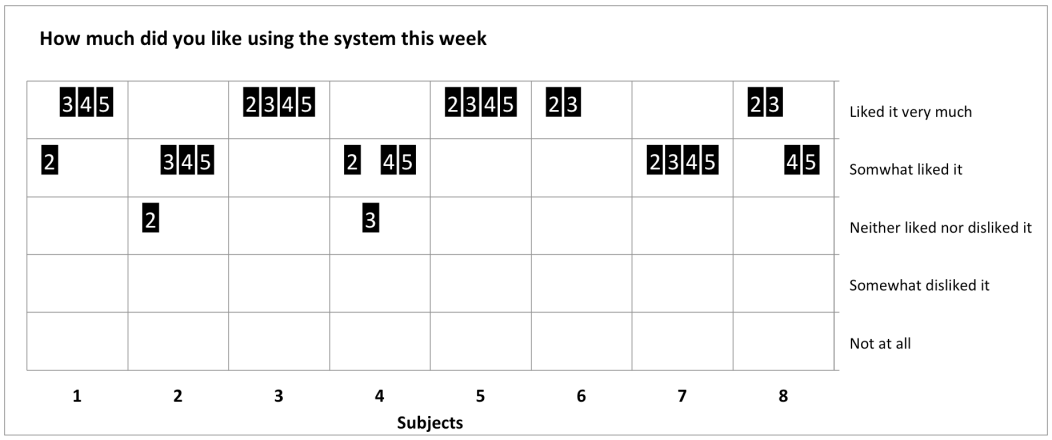
APPENDIX B

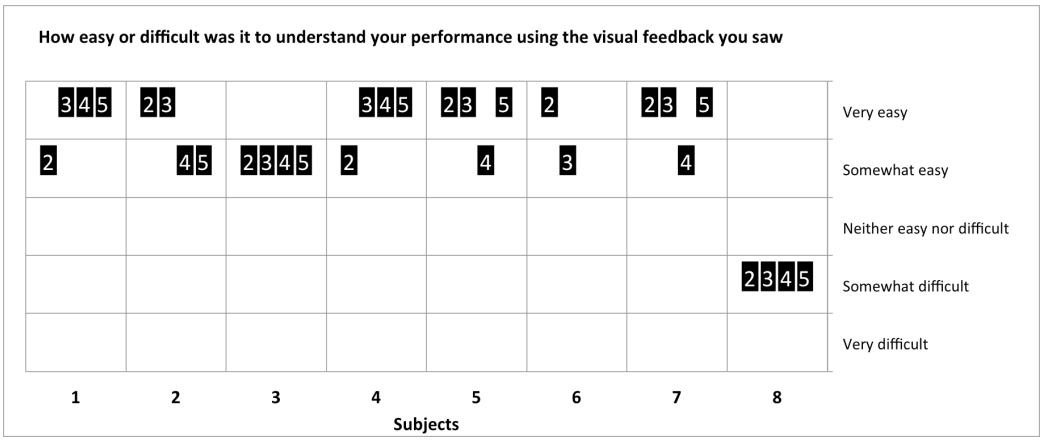
PARTICIPANT RESPONSES TO HAMRR SYSTEM'S EXPERIENCE QUESTIONNAIRE

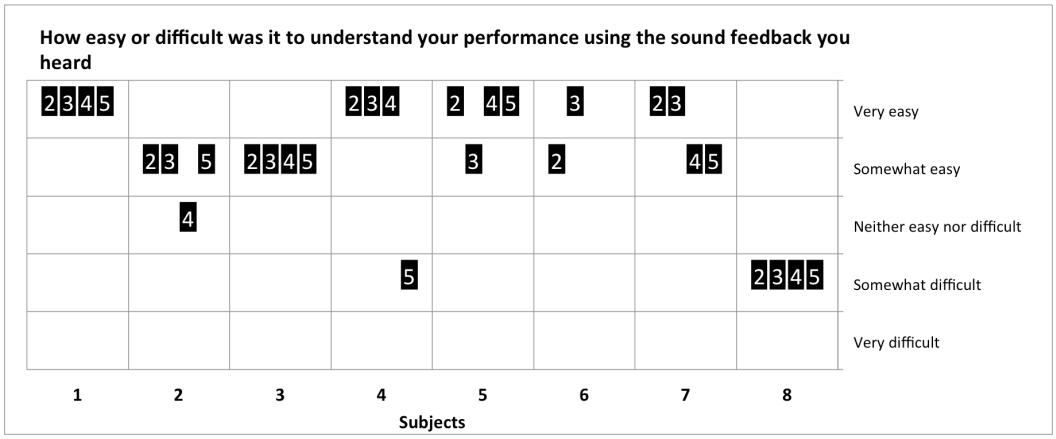

How did you feel about the amount of therapy (number and duration of sessions) this week
Too much
A little more than desirable
About right
Almost enough
Too little
1 2 3 4 5 6 7 8
Subjects

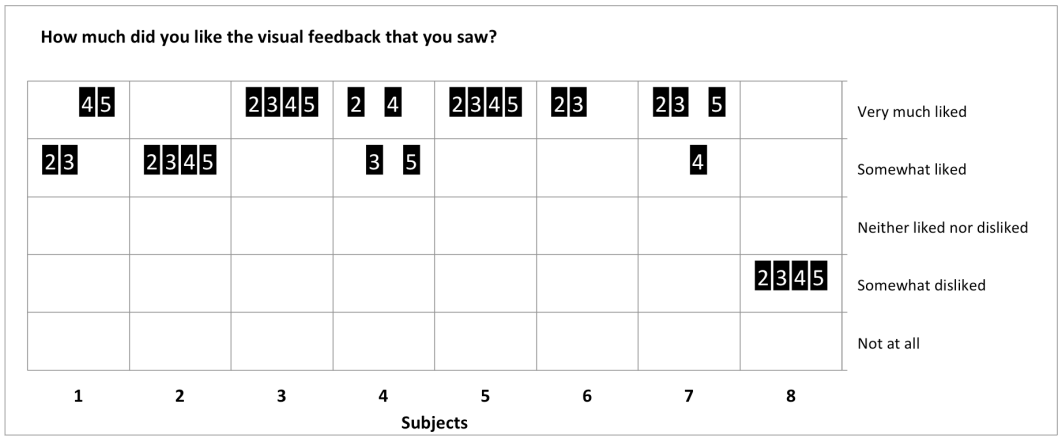

Overall, how challenging was it to perform the training tasks you were asked to complete
Very easy
Somewhat easy
Neither easy nor difficult
Somewhat difficult
Very difficult
1 2 3 4 5 6 7 8
Subjects

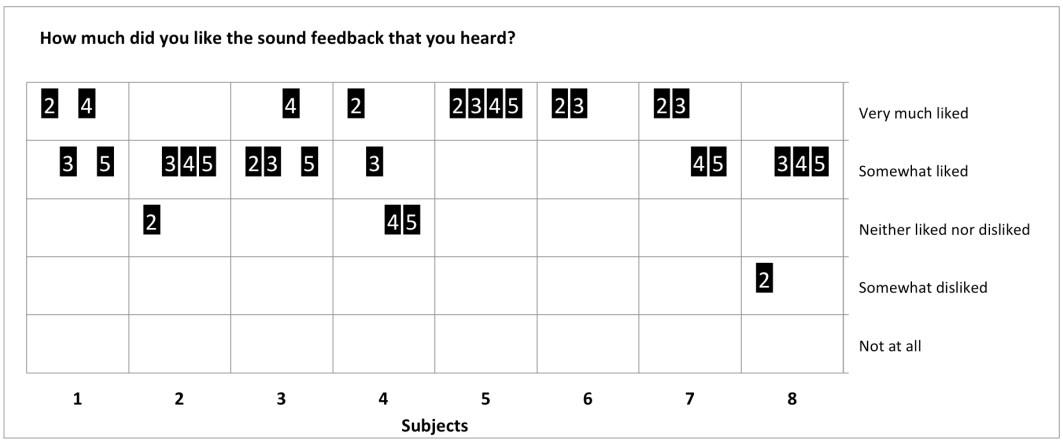

Overall, how easy or difficult was it to understand how to use the system
(e.g. directions on target setup, directions to complete task)
Very easy
Somewhat easy
Neither easy nor difficult
Somewhat difficult
Very difficult
1 2 3 4 5 6 7 8
Subjects

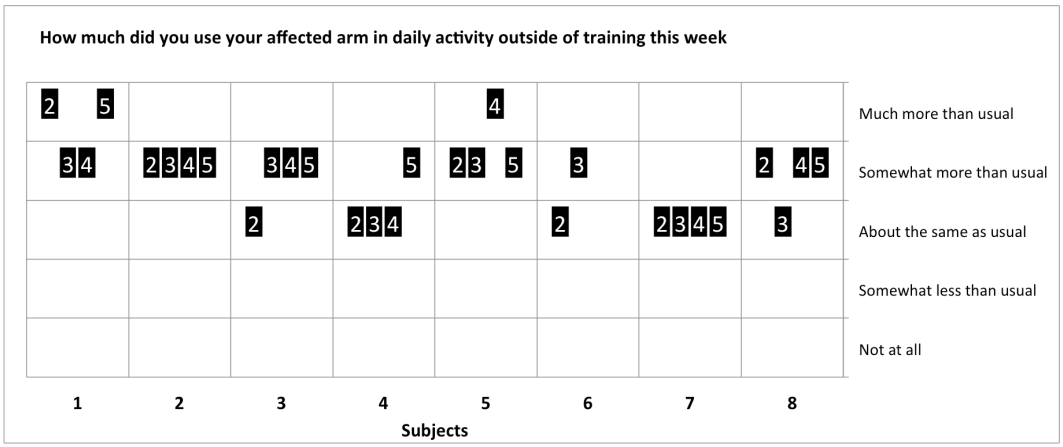

How much did you like using the system this week
Liked it very much
Somwhat liked it
Neither liked nor disliked it
Somewhat disliked it
Not at all
1
2
3
4
5
6
7
8
Subjects

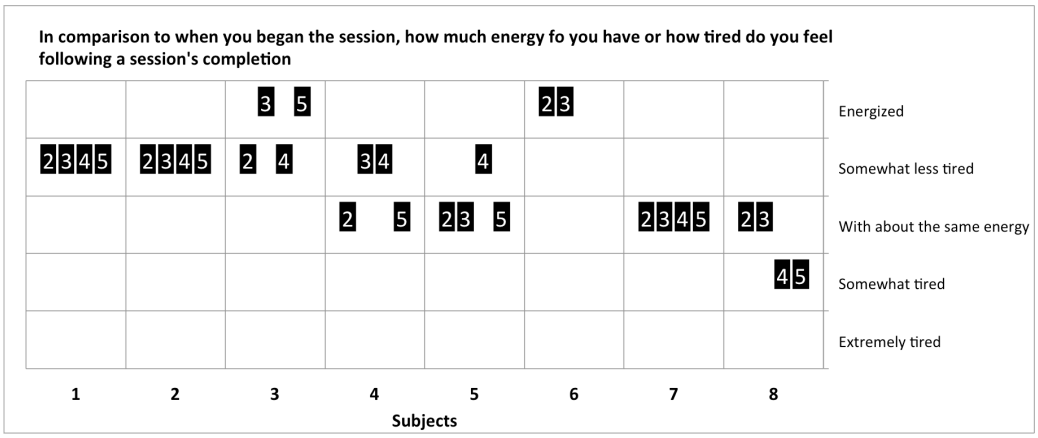

How easy or difficult was it to understand your performance using the visual feedback you saw
Very easy
Somewhat easy
Neither easy nor difficult
Somewhat difficult
Very difficult
1
2
3
4
5
6
7
8
Subjects

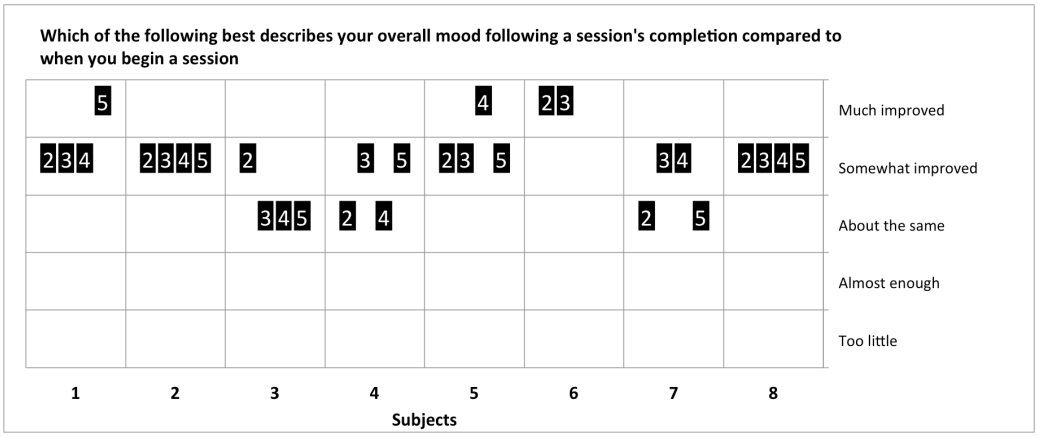

How easy or difficult was it to understand your performance using the sound feedback you heard
Very easy
Somewhat easy
Neither easy nor difficult
Somewhat difficult
Very difficult
1
2
3
4
5
6
7
8
Subjects

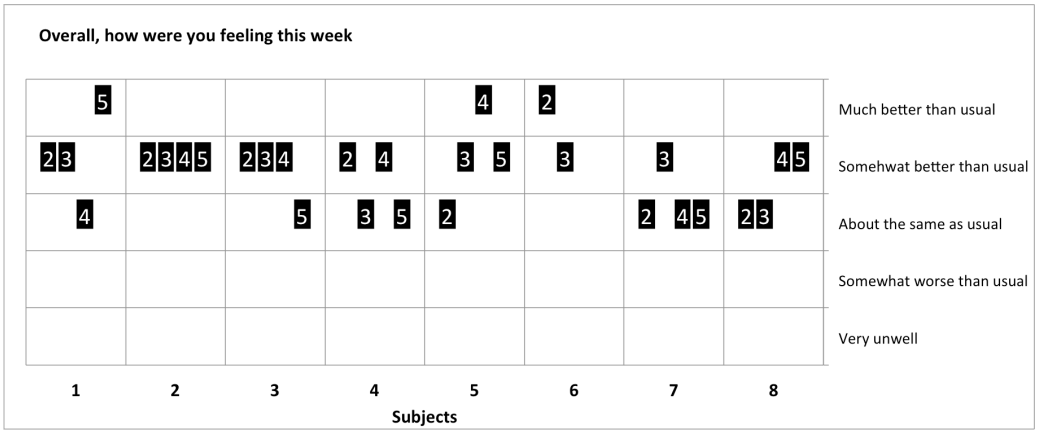

How much did you like the visual feedback that you saw?
Very much liked
Somewhat liked
Neither liked nor disliked
Somewhat disliked
Not at all
1 2 3 4 5 6 7 8
Subjects


How much did you like the sound feedback that you heard?
Very much liked
Somewhat liked
Neither liked nor disliked
Somewhat disliked
Not at all
1 2 3 4 5 6 7 8
Subjects


How much did you use your affected arm in daily activity outside of training this week
Much more than usual
Somewhat more than usual
About the same as usual
Somewhat less than usual
Not at all
1 2 3 4 5 6 7 8
Subjects


In comparison to when you began the session, how much energy fo you have or how tired do you feel following a session's completion
Energized
Somewhat less tired
With about the same energy
Somewhat tired
Extremely tired
1
2
3
4
5
6
7
8
Subjects


Which of the following best describes your overall mood following a session's completion compared to when you begin a session
Much improved
Somewhat improved
About the same
Almost enough
Too little
1
2
3
4
5
6
7
8
Subjects


Overall, how were you feeling this week
Much better than usual
Somehwat better than usual
About the same as usual
Somewhat worse than usual
Very unwell
1
2
3
4
5
6
7
8
Subjects

APPENDIX C

ADDITIONAL FEEDBACK COMPONENTS USED IN THE CLINICAL AMRR SYSTEM

Body Function Level Category: Joint function

Movement Challenge: Many stroke survivors cannot achieve the appropriate timing or range of forearm pronation to complete a reach and grasp task.

Feedback Components: Feedback on forearm rotation is related to end-point activity by controlling the angle of image orientation while particles come together to form the image. Image rotation is controlled by the difference between reference forearm orientation angles at a given distance to the target and the observed forearm orientation. Excessive supination causes clockwise rotation, while excessive pronation causes counter-clockwise image rotation. The size of the rotated image communicates where forearm rotation error occurred relative to distance from target. Examples are provided in Video 8 in Appendix E.

Principles Applied: *Visual* feedback communicates forearm spatial orientation in an *explicit* manner, which provides *concurrent*, *continuous* information throughout the reach to assist the participant's *online control*.

Movement Challenge: Many stroke survivors have difficulty with sufficiently extending the elbow and appropriately timing elbow extension.

Feedback Components: Percentage of elbow extension is mapped to a musical sequence performed by a digitized orchestra.

Principles Applied: Communication of elbow extension is provided as *audio* feedback to assist with timing of movement. Percentage elbow extension is mapped in a *continuous* manner, which communicates changes in magnitude of extension within a reach. Elbow extension feedback is provided *concurrently* to movement and may be used for *online control* and/or memory of its temporal relationship to other mappings can be used for *feedforward* planning. Underscoring achievement with an increasingly rich orchestral sound is a standard technique of film scoring (Adler, 1989). Through *implicit* information processing, memory of successful reaches may be compared with the orchestral quality of other reaches within a set. Examples are provided in Video 8 in Appendix E.

Body Function Level Category: Upper extremity joint correlation

Movement Challenge: Lack of intersegmental joint coordination while reaching for an object in three-dimensional space often results in inappropriate timing of movement at each joint.

Feedback Components: The relationship among different audio mappings connects individual joint function to end-point behavior. During a successful reach, as the target is approached, the rhythmic progression driven by the end-point decreases in speed, and the volume and richness of orchestral strings mapped to elbow extension increases. The peak of orchestral richness is reached at the completion of the grasp and is synchronous to the image completion, the music progression resolution, and the sounding of the success cue (triangle sound. The orchestral sound and foreground music follow the same harmonic progression, which facilitates their integration. The memory of this desired synchronization assists the learning of a coordination schema for elbow extension in relation to end-point trajectory, velocity, and goal completion. Other body function level feedback events, such as the compensation indicator sounds, can also be placed in time along the course of the reach relative to the rhythmic and harmonic musical progression driven by the end-point, and/or related to the lack of orchestral sound. Through experience with the feedback over time, memory of this relationship may occur as an *extracted* information process by the user. Examples are provided in Video 9 in Appendix E.

Principles Applied: Music (*audio*) is a very effective communicator of time relations between separate but parallel events (Yantis, 2000). Multiple relationships between musical lines (e.g., foreground melody versus background accompaniment) and individual sounds (e.g., percussive sounds related to body function) can be easily observed in by listeners *concurrent* to movement and remembered for *extracted* processing after the event (Thaut, 2007; Jaques-Dalcroze, 2007). The intuitive memorization of the musical relationships (McAdams & Bigand, 1993; Levitin, 2006) can facilitate *feedforward* planning. *Continuous* feedback streams that should be correlated are given different individual characteristics (e.g. timbre, rhythm) but follow a similar harmonic progression. *Intermittent* feedback indicators are used that can be related to *continuous* detailed feedback yet can still be identified as separate events.

APPENDIX D

DEFINITIONS OF FEATURES USED IN HAMRR SYSTEM TRAINING

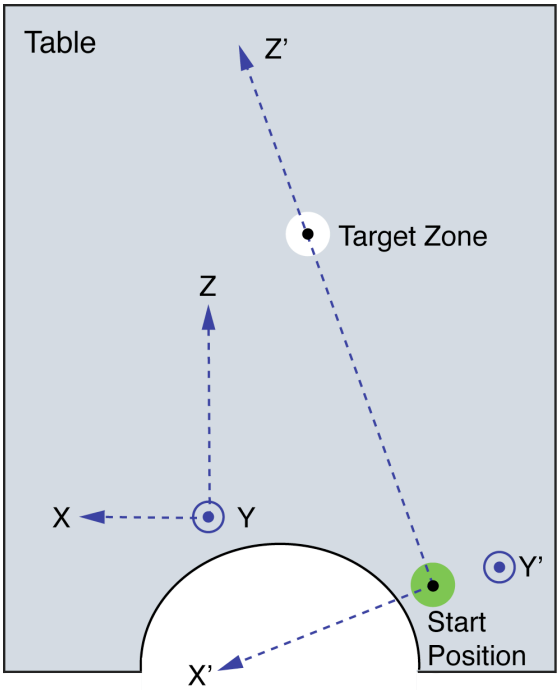
The three levels of training focus on evaluating and providing feedback on the following components of movement:

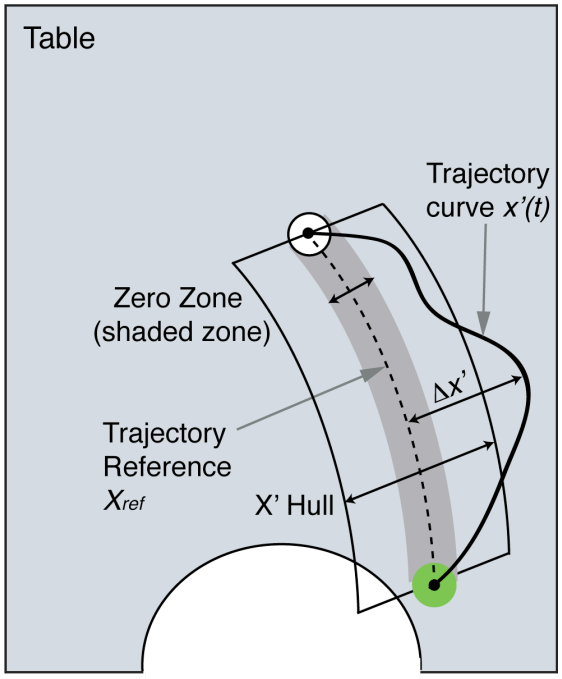
- Reach path
- Reach speed
- Hand manipulation of target
- Compensation
- Transport

Reach path

Operational definition: spatial deviation of the hand from the averaged unimpaired ideal

1. *Path in Level 1 (individual action)*





X raw error (Δx' in the fig.)	Horizontal deviation (mm) from the reference trajectory path
Y raw error	Vertical deviation (mm) from the reference trajectory path
X (or Y) Normalized Error	Horizontal (or vertical) deviation from the reference, normalized to a range of 0 to 1. Any deviation within the zero zone results in a value of 0. Any deviation larger than the hull results in a value of 1. Any deviation between the zero zone and the hull is linearly mapped to a value between 0 and 1

The hull is an adjustable bandwidth for determining how sensitive the system is to the participant's deviation from the unimpaired ideal.

2. *Path in Level 2 (across a group of 5 repetitive actions)*

The overall path quality of 5 repetitive actions may be classified as efficient, curved or segmented. The system classifies each reach in level 2 by selecting the highest confidence measure paired with a path quality. For example, if the curved confidence measure were 0.5 and the segmented confidence measure were 0.8, the action would be classified as segmented.

Curved	Total magnitude of deviation (vertical and horizontal)/total number of deviation points
Segmented	Three factors determine the confidence measure: Compute the number of direction changes, magnitude of direction changes, and the ratio of magnitude of direction changes between different sides.
Efficient	Not curved AND not segmented

3. Path in Level 3 (within a complex task, either a sequential or transport task)

Path Ratio	Compute the length of the straight line between the hand's starting point and the first target location, and the first target location to the second target location, as the baseline. Compute the length of the actual reaching path and divide by the baseline to yield the path ratio. Path ratios equal to or smaller than a reference of 1 are normalized to zero and path ratios equal to or larger than 2.5 times the reference path ratio are normalized to one.

Reach speed

Operational definition: fluidity of movement over time

1. *Speed in Level 1 (individual action)*

Speed	Hand Speed X, Hand Speed Y, Hand Speed Z: Individual velocity (meters per second) in a given spatial dimension. Total Speed: Real time speed magnitude (meters per second). Normalized Speed: Real time speed mapped from 0 – 1, where 1 represents a given "Velocity Peak" value

2. *Speed in Level 2 (across a group of 5 repetitive actions)*

Too fast	Compare each point to the reference speed based on its percentage z prime (distance to target location). Count all the points that are faster than the positive zero zone for this reference. Calculate the ratio of number of points of too fast movement/number of points of total path
Too slow	Compare each point to the reference speed based on its percentage z prime

	(distance to target location). Count all the points that are slower than the negative zero zone for this reference. Calculate the ratio number of points of too slow movement/number of points of total path
Not smooth	Compute the jerkiness of the movement and calculate the ratio of jerkiness to the reference jerkiness. Use the ratio to compute the confidence of jerky movement.

3. *Speed in Level 3 (within a complex task, either a sequential or transport)*

Completion time	Compute the completion time of the task and calculate the ratio with respect to the reference completion time. Use the ratio to compute the quality of completion time. Ratios equal to or less than one are normalized to be zero and ratios larger than 2.5 are normalize to be one.
Speed phase	Compute the quality of speed phase by finding the number of significant local minimums in speed. The score of a movement with a number of phases less than or equal to the reference is normalized to zero and the score of a movement with a number of phases larger than 2.5 times the reference is normalized to one.

Hand manipulation of targets

Operational definition: touch or oppose and squeeze (adequate force generation and opposition of thumb and fingers)

1. *Hand manipulation of targets in Level 1 (individual action)*

Flat or Button object	Physical contact of any part of the hand to the sensing surface of the object
Cone object	Activation of opposing sensors within the top 3 sensor rows: Because the top row only has 3 sensors, any 2 of the top row may be activated for grasp success. For the middle two rows, because there are 4 sensors, they have to be separated by 1 sensor to be considered opposing.
Lift object	Activation of opposing sensors within any row: Each row has 8 sensors, so they activated sensors have to be separated by 2 or 3 sensors to be considered opposing.

2. *Hand manipulation of targets in Level 2 (across a group of 5 repetitive actions)*

Any object	Number of successful touches or grasps (depending on object type) out of the total number of efforts 1-2 Grasps: Severe 3-4 Grasps: Moderate Completed 5: Good

3. *Hand manipulation of targets in Level 3 (within a sequence task) or transport task)*

Any object	Success of touch or grasp (depending on object type) of each object involved in the task

Torso Compensation

Operational definition: excessive body movement

1. *Torso compensation in Level 1 (individual action)*

Compensation is determined by summing the three following components (with weights based on percentage z prime (distance of hand to target))

Chair Total	Real time total amount of pressure (in terms of changes in resistance of sensors) applied to the 6 chair back sensors. This is a real time measure of the sum of all six sensors divided by the maximum sensor readings that the chair could have. Thus, if the score were 1, that means maximum pressure is applied, anything less than that would reduce the number to 0, which corresponds to the smallest sensor reading.
Compensation Angle	Amount of torso movement forward or backward (degrees) from calibrated rest orientation of torso. A linear function relates how these angles change as a function of percentage z prime (distance of hand to target), which provides a reference to compare the participant's angle to determine if compensation is occurring.
Twist Angle	Amount of torso twist rotation (degrees) from calibrated rest orientation of torso. A linear function relates how these angles change as a function of percentage z prime (distance of hand to target), which provides a reference to compare the participant's angle to determine if compensation is occurring.

2. *Torso compensation in Level 2 (across a group of 5 repetitive actions)*

Overall compensation	Percentage of time of an effort in which the torso is compensating

3. *Torso compensation of targets in Level 3 (within a complex task, either a sequential or transport task)*

Overall compensation	Percentage of time of an effort in which the torso is compensating

Transport

Operational definition: Disrupted movement of an object from one location to another

Transport is trained only with the cylindrical portable object. Transport training first focuses on lifting the object to a predetermined height (in levels 1,2) before also transporting the object laterally from one target location to another (level 3).

1. *Vertical lift in Level 1 (individual action)*

Vertical Lift Success	Track if the location of the cylindrical object is higher than a predetermined threshold. The lift height is slightly higher than the height that the lift object would be if it sits on the off the table platform object (used in level 3 transport training).

2. *Vertical lift in Level 2 (across a group of 5 repetitive actions)*

Overall Vertical Lift Successes	Overall vertical lift success is determined from a combined score that combines successful lifts (lifting the object above the threshold) and partial lifts (lifting some height off the table, but not the full height). Complete lifts are assigned a value of 2, partial lifts a value of 1. The scores are summed up and divided by 10 (the maximum score possible: 5 reaches with all successful reaches). This value is then compared to the sensitivity thresholds for the level 2 lift classifier (e.g. 0.4 for low sensitivity, 0.8 for high sensitivity)

3. *Transport in Level 3 (within a complex task, only the transport task)*

Transport from one target object location to another	Quality of transport is derived from the path quality in level 3, speed quality in level 3, and is conditional to if the participant successfully deposits the object.

APPENDIX E

LIST OF VIDEOS

All videos have sound unless noted otherwise

Video 1

file1_clinicalAMRRDemo.mov

This video shows a demonstration of the clinical AMRR system in use with a stroke survivor and supervising therapist. Participant is shown performing interactive reaches to a cone.

Video 2

file2_homeAMRRDemoInstructionAndSet.mov

This video shows a demonstration of the home-based AMRR system in use with a stroke survivor. Participant is shown receiving instructions, followed by performance of one interactive Level 1 set of reaching to grasp and lift a portable cylinder.

Video 3 (no sound)

file3_homeAMRRLevel1Set.mov

This video shows a demonstration of the home-based AMRR system in use with a stroke survivor. Participant is shown performing an interactive Level 1 set of reaching to touch a flat object.

Video 4 (no sound)

file4_homeAMRRLevel2Set.mov

This video shows a demonstration of the home-based AMRR system in use with a stroke survivor. Participant is shown performing an interactive Level 2 set of reaching to grasp a cone.

Video 5

file5_homeAMRRLevel3Set.mov

This video shows a demonstration of the home-based AMRR system in use with a stroke survivor. Participant is shown performing an interactive Level 3 set of reaching to grasp and transport the cylinder between two locations.

Video 6

file6_homeAMRRTargetSetup.mov

This video shows a demonstration of the home-based AMRR system in use with a stroke survivor. Participant is shown setting up the targets used for training.

Video 7

file7_clinicalAMRRFeedbackForTrajectoryAndSpeed.mov
This video shows the clinical AMRR feedback for trajectory performance and speed. Video depicts the image formation and plays the musical phrase generated when a participant performs (1) an efficient reach, followed by (2) a reach with a large horizontal trajectory deviation to the right that generates image stretching and a detuning musical phrase, followed by (3) a slow reach without a prominent rhythmic shape.

Video 8

file8_clinicalAMRRFeedbackForForearmElbowCompensation.mov

This video shows the clinical AMRR feedback for joint function and compensation. Video depicts (1) image rotation when a participant incorrectly times forearm rotation, (2) the orchestral accompaniment generated when a participant extends his elbow while performing an efficient reach, (3) the shoulder compensation sound generated when a participant uses excessive shoulder compensation during the reach, and (4) the torso compensation sound generated when a participant uses excessive torso compensation during the reach.

Video 9

file9_clinicalAMRRFeedbackForJointCorrelation

This video shows the clinical AMRR feedback demonstrating different aspects of joint correlation. Video depicts (1) image formation and plays the musical phrase with orchestral accompaniment generated when a participant extends his elbow while performing an efficient reach, and (2) depicts image formation, stretching, and summary of error, and plays the shoulder compensation sound amidst the musical phrase, generated when a participant uses excessive shoulder compensation during the reach, and as a result performs related trajectory deviations.

Video 10 (no sound)

file10_homeAMRRFeedbackLevel1NegativeVerticalError.mov

This video shows the home-based AMRR Level 1 visual feedback for negative vertical trajectory error. Rocks are depicted to have sunken underwater. The first third of the path shows negative vertical error with severe horizontal error, the second third of the path shows only negative vertical error, and the final third shows negative vertical error with mild horizontal error.

Video 11 (no sound)

file11_homeAMRRFeedbackLevel1Lift.mov

This video shows the home-based AMRR Level 1 visual feedback for a successful lift with an efficient reaching path. The straight path of rocks indicates no spatial deviations were made. The clearance of the fog indicates the portable object was lifted beyond a height threshold.

Video 12 (no sound)

file12_homeAMRRFeedbackLevel2PathGraspTags.mov

This video shows the home-based AMRR Level 2 visual feedback for overall path and grasp performance. Video depicts feedback for the following types of overall performance: (1) efficient path, (2) slight curvature, (3) severe curvature, (4) slight segmentation, (5) severe segmentation, (6) low grasp completion rate, (6) medium grasp completion rate, (7) high grasp completion rate.

Video 13

file13_homeAMRRFeedbackLevel3Sequence.mp4

This video shows the home-based AMRR Level 3 audiovisual feedback for overall efficiency of a sequence task. Video depicts (1) efficient performance, (2) slightly inefficient performance, and (3) severely inefficient performance. Islands shown reflect two flat objects.

Video 14

file14_homeAMRRFeedbackLevel3Transport.mp4

This video shows the home-based AMRR Level 3 audiovisual feedback for overall efficiency of a transport task. Video depicts (1) efficient performance, (2) slightly inefficient performance, and (3) severely inefficient performance. Islands shown reflect a portable grasp object transported back and forth between two locations.

APPENDIX F

IRB APPROVAL DOCUMENTS

ASU IRB approval for Clinical AMRR study

ASU Arizona State University
RESEARCH AND ECONOMIC AFFAIRS

Office of Research Integrity and Assurance

To:	Thanassis Rikakis BKYD
From:	Carol Johnston, Chair Biosci IRB
Date:	01/06/2009
Committee Action:	**Expedited Approval - Limited**
Approval Date:	01/06/2009
Review Type:	Expedited F3
IRB Protocol #:	0812003572
Study Title:	Mixed Reality Rehabilitation for Stroke Patients
Expiration Date:	01/05/2010

The above-referenced protocol was granted limited approved following expedited review by the Institutional Review Board.

This approval is limited, pending receipt of the Banner Baywood Medical Center IRB approval. No human subjects enrollment

can occur until the Arizona State University IRB has recieved and reviewed the Banner Baywood IRB approval.

TIt is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. You may not continue any research activity beyond the expiration date without approval by the Institutional Review Board.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Biosci IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Biosci IRB. The new procedure is not to be initiated until the IRB approval has been given.

Please retain a copy of this letter with your approved protocol.

Banner IRB approval for Clinical AMRR study



January 20, 2009

Paul Blake, M.D.
Attn: Barbara Lambeth, Paul Blake, M.D.
Rhodes Rehabilitation Institute
Banner Baywood Medical Center
6644 E. Baywood
Mesa, AZ 85206

RE: **Project # 08-09-0001**
Mixed Reality Rehabilitation for Stroke Patients
iRIS Reference # 007385
IRB Expedited Approval – New Protocol, Informed Consent and Authorization to Use or Disclose PHI in Research

Dear Dr. Blake:

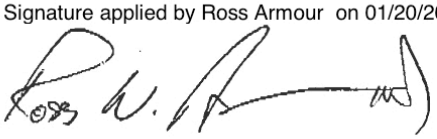
This letter serves to notify you that the above referenced Protocol, Informed Consent, and Authorization to Use or Disclose PHI in Research received expedited review and approval by Ross Armour, MD, Chair of the Banner Health Institutional Review Board (Western Region Panel) on January 20, 2009 for conduction at Banner Baywood Medical Center. This expedited review was performed in accordance with 21CFR56.110 (b) and 45CFR46.110(b). This study has received approval for one year. The FDA requires that all studies be reviewed at least annually. The final approved, stamped Informed Consent is available electronically. You must use photocopies of this Informed Consent exclusively. A copy of the signed Informed Consent document must be placed in the patient's medical records.

The Board's approval to conduct your study will expire on 1/19/2010. The IRB requests that you submit a Continuing Review report one month prior to the January 2010 IRB meeting. This allows time for processing and review prior to the IRB expiration date of the study. A Closing report is required upon completion of the project. The occurrence of adverse reactions/events must be reported to the Board in writing within 3 days of the occurrence. Any changes in the study protocol, unusual events, results of the study or any additional information relative to the study must be submitted to the Board. In the event the study results are published, please send a copy to the Banner Health Research Administration so it may be included in the file. A copy of this letter will be placed in the study file.

The Board appreciates your participation in research. If you have any questions, please contact Michelle Faber, CIM, IRB Coordinator, at 970-346-3722.

Sincerely,

Signature applied by Ross Armour on 01/20/2009 11:31:55 AM GMT-07:00



Ross Armour, MD

212

ASU IRB approval for Home-based AMRR user testing of feedback

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Todd Ingalls MCENT
From:	Carol Johnston, Chair Biosci IRB
Date:	04/01/2013
Committee Action:	**Renewal**
Renewal Date:	04/01/2013
Review Type:	Expedited F4 F7
IRB Protocol #:	1104006325
Study Title:	Determining the Efficacy of Real-time and Summary Feedback for Reaching tasks
Expiration Date:	04/29/2014

The above-referenced protocol was given renewed approval following Expedited Review by the Institutional Review Board.

It is the Principal Investigator's responsibility to obtain review and continued approval of ongoing research before the expiration noted above. Please allow sufficient time for reapproval. Research activity of any sort may not continue beyond the expiration date without committee approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol on the expiration date. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

This approval by the Biosci IRB does not replace or supersede any departmental or oversight committee review that may be required by institutional policy.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Biosci IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Biosci IRB. The new procedure is not to be initiated until the IRB approval has been given.

Please retain a copy of this letter with your approved protocol.

EMORY UNIVERSITY | Institutional Review Board

TO: Steven Wolf, MD
Principal Investigator
Rehab Medicine - Main

DATE: February 10, 2014

RE: **Continuing Review Expedited Approval**
CR1_IRB00062700

IRB00062700
Adaptive Rehabilitation using Mixed Reality at Home

Thank you for submitting a renewal application for this protocol. The Emory IRB reviewed it by the expedited process on 02/10/14, per 45 CFR 46.110, the Federal Register expeditable category F(9), and/or 21 CFR 56.110. This reapproval is effective from **02/19/14** through **02/18/15** . Thereafter, continuation of human subjects research activities requires the submission of another renewal application, which must be reviewed and approved by the IRB prior to the expiration date noted above.

Documents reviewed with this application:

- Manual of Procedures 5-01-13
- Consent Form clean 5-01-13
- HIPAA Authorization clean 5-01-13

Any reportable events (e.g., unanticipated problems involving risk to subjects or others, noncompliance, breaches of confidentiality, HIPAA violations, protocol deviations) must be reported to the IRB according to our Policies & Procedures at www.irb.emory.edu, immediately, promptly, or periodically. Be sure to check the reporting guidance and contact us if you have questions. Terms and conditions of sponsors, if any, also apply to reporting.

Before implementing any change to this protocol (including but not limited to sample size, informed consent, and study design), you must submit an amendment request and secure IRB approval.

In future correspondence about this matter, please refer to the IRB file ID, name of the

Principal Investigator, and study title. Thank you.

Sincerely,

Scott S. Katz, MS
Analyst Assistant
This letter has been digitally signed

CC:	Blanton	Sarah	Rehab Medicine - Main
	Murphy	Susan	Rehab Medicine - Main
	Reiss	Aimee	Rehab Medicine - Main
	Sahu	Komal	Rehab Medicine - Main

ASU deferral to Emory U. IRB for Home-based AMRR study



Nicole Lehrer <nicole.lehrer@gmail.com>

RE: IRB agreement with RIC

Debra Murphy <Debra.Murphy@asu.edu> Wed, Dec 5, 2012 at 11:08 AM
To: Pavan Turaga <pturaga@asu.edu>, Steven Wolf <Steven.L.Wolf@asu.edu>
Cc: "Aimee Reiss (aimee.reiss@emory.edu)" <aimee.reiss@emory.edu>, Zev Rymer <zevric@gmail.com>, Margaret Duff <mrduff@asu.edu>, Thanassis Rikakis <trikakis@andrew.cmu.edu>, "Nicole Lehrer (Student)" <Nicole.Lehrer@asu.edu>, "Michael Baran (Student)" <Michael.Baran@asu.edu>

ASU will defer to Emory as the IRB of record and I am the signatory for ASU on the affiliation agreement.

Thanks.

Deb

RIC IRB approval for Home-based AMRR study

Institutional Review Board Office
Northwestern University
Biomedical IRB
750 North Lake Shore Drive
Suite 700
Chicago, Illinois 60611
312-503-9338

Social and Behavioral Sciences IRB
600 Foster Street
Chambers Hall, Second Floor
Evanston, Illinois 60208
847-467-1723

NORTHWESTERN UNIVERSITY

4/10/2013

Dr. William Rymer
Physical Medicine and Rehabilitation
Suite 1396 345 East Superior
Chicago IL 60611
w-rymer@northwestern.edu

IRB Project Number: STU00074789
Project Title: Adaptive Rehabilitation using Mixed-reality at Home: The ARM at Home Study
Project Sites:

Rehabilitation Institute of Chicago (RIC)

Sponsor Information (Grant #, if applicable):

View National Institute of Health #5 R24 HD 050821-09

Submission Considered: New Submission **Submission Number:** STU00074789
Study Review Type: Full IRB Review
Meeting Date: 03/21/2013
Panel: Panel D
Status: APPROVED **Approval Period:** (4/10/2013 - 3/20/2014)

Dear Dr. Rymer,

The IRB considered and approved your submission referenced above through 3/20/2014. As Principal Investigator (P.I.), you have ultimate responsibility for the conduct of this study, the ethical performance of

the project, and the protection of the rights and welfare of human subjects. You are required to comply with all NU policies and procedures, as well as with all applicable Federal, State and local laws regarding the protection of human subjects in research including, but not limited to the following:

- Not changing the approved protocol or consent form without prior IRB approval (except in an emergency, if necessary, to safeguard the well-being of human subjects).
- Obtaining proper informed consent from human subjects or their legally responsible representative, using only the currently approved, stamped consent form.
- Promptly reporting unanticipated problems involving risks to subjects or others, or promptly reportable non-compliance in accordance with IRB guidelines.
- Submit a continuing review application 45 days prior to the expiration of IRB approval. If IRB re-approval is not obtained by the end of the approval period indicated above, all research related activities must stop and no new subjects may be enrolled.

IRB approval includes the following:

Written Consent Form/Consent Form and Authorization for Research:

Name
STU74789 Consent Form v. 4-10-2013.docx

Protocol Document:

Name
Protocol_Rymer_STU74789_v.02.11.2013.docx

Recruitment Materials (Note- the investigator is responsible for complying with applicable departmental or NU policies regarding use of bulk e-mail for recruitment purposes):

Name
PhoneScreenScript.docx

Survey/Questionnaires:

Name
MAL.pdf
Perception.pdf

Interview Scripts:

Name
Experience Questionnaire