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Virtual Motor Spaces: Exploring how to amplify movements in VR stroke rehabilitation to aid patients with upper limb hemiparesis.

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***Abstract*— Varying severity of upper limb hemiparesis provide challenge how to design player input control in virtual reality (VR) rehabilitation systems. We designed virtual motor spaces as a novel input method in VR which amplify limited hand movement for a Whack-A-Mole game. Results from an initial pilot study showed that participants were able to reach the same number of targets in the same amount of time. The virtual motorspaces aim to facilitate rehabilitation and for neuropsychological comparison of patient performance despite differing severity of hemiparesis.**

I. INTRODUCTION

Upper limb (UL) hemiparesis and spatial neglect are common impairments after stroke. Around 50 percent of patients with stroke suffer from impaired UL motor function, one-third experiencing severe impairment [1]. Unilateral spatial neglect (USN) is prevalent in 23–46% of stroke survivors [2], [3]. Both conditions frequently occur together, which has a detrimental influence on recovery and the ability to perform activities of daily living.

Conventional methods for USN diagnosis include pen and paper, such as the bell test [4] and the Apples test [5]. Adaptations of conventional tests to immersive virtual reality (VR) systems show promise for enhanced diagnosis and treatment of USN and motor impairments [6], [7], [8]. Head-mounted displays occupy the patients entire visual field, which allow for full control of visual information during treatment. The VR systems track body movement, which enable analysis of movement trajectories and midline diagnostics [6].

Virtual Reality systems create realistic tangible natural mapping, through spatial alignment of players' hands or virtual controllers and direct manipulation of virtual objects. However, virtual reality systems must encourage hand movement, while being adaptable to a broad range of UL hemiparesis, from slightly impaired dexterity to almost no active movement of the affected hand. VR rehabilitation systems must also be designed to accomodate UL and USN patients' inability to perceive and/or react to stimuli form the contra-lesional side caused by the USN.

Individual movement limitations challenges direct manipulation paradigms in VR, because the targets may become out of reach. Virtual pointing paradigms can overcome movement limitations, but make targets too easy to reach, which discourages hand movement necessary for the treatment. If movement limitations are not addressed, patients may be at disadvantage to complete tasks in VR, which result in a missing frame of reference needed to perform data analysis and comparison of patient movements, for e.g. midline diagnostics [6].

We explored this tension point in a VR Whack-A-Mole game, designed for UL and USN treatment [9] (shown in Figure 1). We propose a novel VR interaction paradigm called *virtual motor space*, which transforms movement of the controller in a limited space to the movement of a virtual cursor on a vertical wall which used the patients' entire visual field of view. The virtual cursor is bound to the player's controller by a laser in an extended arm metaphor [10], but does not react to pointing, to encourage more arm movement. Movement within the virtual motor space creates an amplified corresponding movement on the Whack-a-mole wall similar to control-display gain. This feature enable patients with a broad range of UL motor impairments to play Whack-A-Mole under similar conditions (identical wall size and appearance). To assess how the virtual motor spaces affected task performance, a pilot study tested 3 different sizes of virtual motor spaces with 14 healthy subjects. The results showed that the virtual motor spaces increased movement activity, while achieving similar mean hit rate and reaction time.

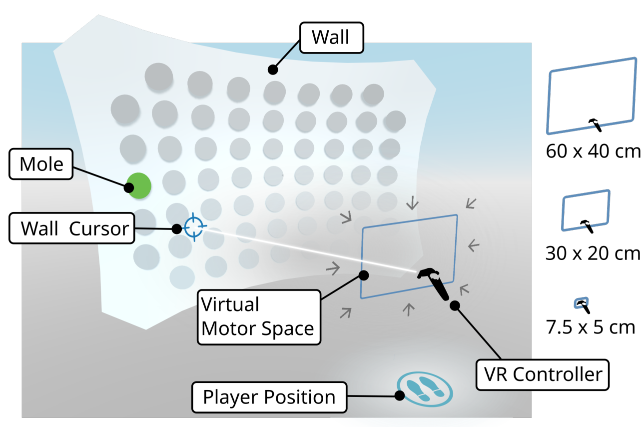

Fig. 1. Illustration of Whack-A-Mole VR. The virtual motor space is a 2D rectangular area close to the player's seated position, which come in three sizes displayed to the right. When players move their VR controller within the virtual motor space, their movements translate to wall cursor movements on the Whack-A-Mole wall. The goal is to move the wall cursor and hit all active (green) moles as fast as possible.

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II. Motor Space Design

The virtual motor space consisted of a two-dimensional world-locked rectangular area, which enabled control of a cursor on the Whack-A-Mole wall, when the user's controller move within its boundaries. The virtual motor spaces in Whack-A-Mole VR were designed and implemented for seated VR gameplay, from e.g. a wheelchair. The virtual motor space dimensions supported three prefixed sizes of small (7.5 cm x 5 cm), medium (30 cm x 20 cm), or large (60 cm x 40 cm), to allow for rigid comparison of movement data. The motor space dimensions could also be altered through a custom calibration, which let players draw the outer boundaries of their own motor range in VR. The left-most, right-most, upper and lower boudnaries of the Whack-A-Mole wall became mapped to the motor space boundaries.

Virtual motor spaces in VR may increase accessibility for patients with UL impairment and USN, but impose several design challenges, compared to other naturally mapped control interfaces.

1) **Visibility:** Visual indication of the virtual motor space, help users locate their position and boundary in VR. However, visual indication introduce peripheral noise into the visual modality, which can distract users from tracking the cursor on the Whack-A-Mole wall and the moles which they need to target.
2) **Loosing track:** If the virtual motor space is smaller than the player's motor space, players may end outside virtual motor space boundaries and loose track of the wall cursor. It is unclear which signifiers are best suited to make players move back within the virtual motor space.
3) **Communicating change:** Motor spaces may change (alter their width and height), as part of treatment program design or by a therapist. However, it is not clear how these changes should be visually communicated to the player in VR.

To solve above challenges, we introduced dynamic visibility and animations. When players were within the boundaries of the motor space, the motor space remained invisible, to let players focus on the wall cursor. The motor space became visible when players moved outside boundaries, and animated arrows to draw players' attention. The motor space became visible for a short while when it changed size and animated the size change.

III. Pilot Study

To benchmark human performance when using virtual motor spaces, 14 healthy subjects (6F/8M, Age: 20-60, M=28.1) played Whack-A-Mole VR using a HTC Vive head-mounted display with three motor space sizes (small, medium and large). Each play session lasted 4 minutes. Participants played the same motor space size for three rounds with their left, right and finally both hands (9 play session total). Moles appeared in similar patterns in all conditions, but the patterns were temporally randomized to counter learning effects. The game logged data continuously while participants were playing. Data was analyzed and post-processed in R studio.

TABLE I

Average mole hit rate, speed and travel distance for each tested motor space with standard deviation in parenthesis.

Motor space	Hit Rate	Reaction Time	Movement
Large	98% (3.2)	1.08s (0.2)	52.2m (5.8)
Medium	99% (1.4)	0.96s (0.2)	26.9m (4.9)
Small	97% (4.4)	1.12s (0.2)	11.8m (7.8)

Benchmark analysis presented in Table I, showed that participants could hit 97-99% of all moles with equivalent speeds with all three motor spaces. Increased motor space size also increased participant hand movement when performing the task.

IV. Next Steps

Future studies, will measure how well motor spaces allow for adaption of Whack-A-Mole for stroke patients with UL impairment or USN. The benchmark will measure more parameters, including time spent outside motor spaces, patient motor space boundaries and eye tracking analysis.

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