ABSTRACT

EFFECT OF ENACTIVE-INTERFACE CONSTRAINTS ON USER BEHAVIOR IN VIRTUAL ENVIRONMENTS

by Henry Ernest Cook IV

An issue that the users face when employing a controller in virtual environments (VE), is effectively using the afforded actions necessary for task-relevant goal achievement. A virtual reality game was used to investigate the link between the physical constraints of a controller-interface, the behavioral (postural) control strategies that develop and subsequent performance within the VE. Postural motion was examined using a motion capture system, and the differences that emerged as a result of the controller interface-order using various synchronicity-non-linear procedures. A significant interaction was found between user performance and controller-interface order. These findings suggest that the constraints of the controller does not necessarily create performance differences at face value though the increase or decrement of performance is grounded on how the user gains information through interacting with the specific controller interface as well as how that interaction shapes their ability to learn, adapt, and develop successful, relevant control strategies.
EFFECT OF ENACTIVE-INTERFACE CONSTRAINTS ON USER BEHAVIOR IN VIRTUAL ENVIRONMENTS

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## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Properties of the Controller</td>
<td>3</td>
</tr>
<tr>
<td>Present Study</td>
<td>7</td>
</tr>
<tr>
<td>METHOD</td>
<td>9</td>
</tr>
<tr>
<td>Participants</td>
<td>9</td>
</tr>
<tr>
<td>Materials</td>
<td>10</td>
</tr>
<tr>
<td>Procedure</td>
<td>11</td>
</tr>
<tr>
<td>RESULTS &amp; DISCUSSION</td>
<td>12</td>
</tr>
<tr>
<td>Performance Data</td>
<td>13</td>
</tr>
<tr>
<td>State Space Plots</td>
<td>14</td>
</tr>
<tr>
<td>Cross Fuzzy Entropy Analysis</td>
<td>15</td>
</tr>
<tr>
<td>Cross Fuzzy Entropy Discussion</td>
<td>17</td>
</tr>
<tr>
<td>Coherence Analysis</td>
<td>17</td>
</tr>
<tr>
<td>Coherence Discussion</td>
<td>18</td>
</tr>
<tr>
<td>Cross-Correlation Analysis</td>
<td>18</td>
</tr>
<tr>
<td>Cross-Correlation Discussion</td>
<td>21</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>22</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>27</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1: Virtual-On Control Schematic Layout................................................................. 31
Table 2: Virtual-On Performance Data................................................................. 32
LIST OF FIGURES

Figure 1............................................................................................................................. 33
Figure 2............................................................................................................................. 34
Figure 3............................................................................................................................. 35
Figure 4............................................................................................................................. 36
Figure 5............................................................................................................................. 37
Figure 6............................................................................................................................. 38
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Introduction

In order to achieve most (if not all goals) in virtual environments (VE), the user must be able to successfully perceive the elements of their surroundings deemed useful for accomplishing specific task-oriented goals. In relation to the use of perceptual information that the VE provides, the user must also appropriately use the capabilities granted by the device that controls their actions within these environments. Due to current technological constraints, the implementation of physical interfaces, such as gaming controllers, are designed to give the user the ability to act in a VE. The use and analysis of a controller provides an interesting focal point that may help confront the reports of decreased task performance and frequent reports of motion sickness in virtual environments (Stoffregen, Hettinger, Haas, Roe, & Smart, 2000). The controllers allow the user to exploit appropriate action-capabilities for the given task, but must also coordinate with the perceptual layout that the user must use to navigate in this environment. Successful coordination, which takes into account the perceptual elements of the environment and the action-capabilities of the user-controller interaction, allows for the user’s activities to reveal the behavior(s) that facilitate reaching the intended goal state(s). Previous research has found that problems tend to emerge when the user implements control strategies that may be inappropriate for the given task or behavioral goals (Littman, Otten, & Smart, 2010).

Commonly found in these unsuccessful attempts to navigate within these virtual environments is perceptual information that the user perceives as usable, even if these capabilities are not truly possible. For example, a door is presented to the user, yet is merely an aesthetic set piece of the environment (Stanney & Hash, 1998; Stoffregen, Bardy, & Mantel, 2006). When examining the issue of the controller and the behavioral strategies that develop through its use, the constraints of the controller used in these environments may provide irrelevant action-capabilities and action-possibilities that prompt the user to initiate actions irrelevant to the current task and goal state (Littman, Otten, & Smart, 2010).

This irrelevant information may aid in the development of maladaptive behavioral control strategies that further disrupt the user’s ability to successfully act in these virtual environments. The user may find that a controller-interface allows for random joystick/button movements/pressing, though the constraints of the task require more structured and precise movements to accomplish the given task (i.e. virtual laparoscopic surgery). Because of this focal
issue, the current study attempts define potential parameters of the physical interface that aid in the development of adaptive control strategies in these environments. Specifically, this study will examine physical controller-interfaces designed specifically for the selected VE, or devices that are more general in purpose, such that it can be used in various VEs. Due to the emphasis of how the user interacts and develops behavioral control strategies with the given device, the influence of order in which the user receives the specific or non-specific interface will also be investigated.

Many studies have provided evidence that control is essential for the appropriate assessment and adaptation of behavioral strategies that enhance performance, and reduce the aversive effects of maladaptive behavioral states (e.g., motion sickness; Dong, Yohishida, & Stoffregen, 2011; Littman et al., 2010; Smart, Johnson, Oates, Littman, Otten, & Vitatoe, in revision; Stanney & Hash 1998). The question and primary purpose of this study is to discover how behavioral control strategies develop through the use of a controller, and quantify these behaviors in relation to the capabilities for action allowed by given controller-interface, i.e., the physical layout and functionality of the device used to interact with an environment.

The success of task-related behavioral goals requires that the individual be proficient in their ability to understand, assess, and interact with their environment, as well as the objects that help compose it. The strength of an organism’s ability to interact with these entities, (such that, the intended goal is accomplished) is determined by the extent that the possibilities for action (affordances; Gibson, 1986; Stoffregen, 2003) that exist within the environment are efficiently recognized, coordinated, and subsequently used by that organism. These affordances are not innate within the organism nor do they reside solely within the environment; instead they emerge from the intersection of the object’s properties and the user’s capabilities.

The implication of the emergent nature of affordances is that they exist regardless of the organism’s awareness of these action-possibilities. Consequently, the successful recognition and application of possible actions are more likely to occur when these actions are aligned with the current behavioral goals. Given this action becomes a necessary mechanism in the process of discovering the appropriate affordances that aid in reaching the specified goal (Stoffregen et al., 2003b; Stoffregen, Bardy & Mantel, 2006). This process of discovering the appropriate affordances derive from the organism’s exploratory behavior and has been referred to as enactive (Stroffregen, Bardy & Mantel, 2006; Varela et al., 1991). The term enaction coined by Varela et
al. (1991) expresses the connection between purposeful perceptual-motor coordinated activity, and prospective control (behavioral regulation in the service of a future goal state; Gibson, 1969); arguing that knowledge is acquired through perceptive/active interactions with the environment. To this extent, it is posited that knowledge is obtained through action whether it is exploratory or purposeful with enaction referring to the means of interaction between the information gained from the environment and the actions that we generate (Varela et al. 1991).

**Properties of the Controller**

The controller is more than a device that guides the user through the simulated environment; it is a tool that ideally affords an array of specific options by constraining the user to employ responses that are specific to the tasks of the environmental goals. The question faced when addressing the specific design and use of a controller is the flexibility and implementation of its relevant action-oriented capabilities that are discovered by the user as they interact with the interface in a VE. Controllers, through consequence of their design, provide specific capabilities that enable purposeful actions that match the affordances and goals within the environment (which I will define as Type-Alpha-capabilities); while also physically constraining the user’s array of possible action-capabilities, (Type-Beta capabilities; e.g., control strategies of a generic controller vs. steering wheel). Most of the research examining user-controller interactive systems, have examined the task constraints of purposeful action (Alpha-capabilities). It is essential to understand the properties of Alpha-capabilities, as this class of behavior-shaping constraints are directly tied to the user’s environment (Rasmussen & Pejtersen, 1995); and thus these constraints define the parameters of possible actions by the user (Smith, Henning, & Smith, 1994).

Though these constraints define the problem-space the user must still develop control strategies (Beta-capabilities) within this space that lead to actions appropriate for reaching the intended goal state. In these situations, both classes of behavior-shaping constraints must be well defined (perceivable) to the user, which will allow appropriate perceptual-motor organization to emerge. In virtual environments these control strategies (beta-capabilities) are commonly developed within a controller-interface. Within each controller lie varying degrees of freedom (DoF) that establishes the capabilities of that interface, and possible actions available to the user. Based on previous research (Stroffregen, Bardy, & Mantel, 2006; Varela et al., 1991; Walker,
Gomer, & Muth, 2007), I would argue that these beta-capabilities exist in two forms: Task-Relevant and Task-Irrelevant. Such that task relevant DoF impose physical constraints that help structure the appropriate afforded action capabilities that synchronize to the specific behavioral task; conversely action capabilities irrelevant to the given task afford actions that are not necessary or intended towards the further progression of specific behavioral goal states. As previously stated, the goal in these situations is to optimally fit the perceptual affordances of the environment (Alpha) with the task-relevant capabilities of the controller (Figure 1).

To conceptualize this model, take for example the simple differences between a joy-stick and a set of buttons that are used in a fork-lift simulator (In regards to Type-Alpha capabilities the joy-stick more accurately depicts the operation of the lift in comparison to pressing an arrangement of buttons used to move and operate the vehicle). When using the joystick there is a more comparable link to the perceived affordances of the VE and the relevant actions that are possible (Bianchi-Berthouze, et al., 2007). In regards to Type-Beta-capabilities the joystick reduces the freedom and flexibility of the user’s action-oriented capabilities, so that the possibility for task-relevant actions initiated in the VE are more likely to emerge in aid of the behavioral task.

Generic designed controllers that come pre-packaged with many current gaming platforms fit no specific scheme, thus universally purposeful and flexible, providing non-task specific actions in support of the intended goal. Littman et al. (2010) stated that users of active-controls successfully adapt to the environmental stimuli by finding the appropriate-task specific behavioral pattern that allows the user to update their usage of perceptual information while actively modifying their behaviors to fit the constraints of the environmental stimuli. It is arguable that the non-task specific behaviors that may persist in these generic controllers are ill-suited in support of the user finding these appropriate-task specific behavioral patterns.

Task-relevant degrees of freedom establish two important capabilities: they synchronize well with that of Type-Alpha-capabilities; while effectively reducing the flexibility of expressed Type-Beta-capabilities, so that capable behavioral actions are related to the intended behavioral goal. These constraints guide relevant action capabilities that develop behavioral patterns aimed towards matching the scheme of the behavioral task as well as providing the perceptual information necessary in assessing the appropriate-task specific behavioral pattern. In addition
this type of DoF can allow for efficient and well modified postural coordination and stability (Riccio & Stoffregen, 1991; Smart, et al., 1998; Stoffregen, Yoshida, Villard, Scibora & Bardy, 2010).

Traditional controls or controls that do not fit the intended purpose of the environment may be too ill-defined and flexible in their design to spur efficient use. This flexibility (degrees of opportunity) may also reduce the user’s ability to discover the appropriate task-specific behavioral patterns that are necessary for adapting to the environment; consequentially this flexibility may induce maladaptive behavioral strategies (Littman, Otten, & Smart, 2010). If these maladaptive strategies remain consistent overtime, it is possible that the user’s behavioral motion will indicate the occurrence of these maladaptive strategies. In these scenarios research has found that the user may instinctually develop more rigid forms of behaviors (reducing postural motion) as a way of reducing the perceptual information to which the user cannot adapt to (instinctual escape mechanisms; Hendriks, Spoor, Jong & Goossens, 2006). Research observing behavioral patterns of motion finds that when the user develops these rigid behavioral patterns, the incidences of maladaptive behaviors are more likely to occur (Littman, Otten, & Smart, 2010; Riccio & Stofregen, 1991; Smart, Stoffregen, & Bardy, 2002; Smart, Otten, & Stoffregen, 2007; Smart, et al., 1998; Stroffregen, et al., 2002; Stoffregen & Smart, 1998).

To test influence of controller capabilities, a novel virtual gaming environment titled, “Cyber Troopers: Virtual-On Ontario Tangram”, developed by the gaming company SEGA was used as the stimulus for this study. Virtual-On Ontario Tangram (VOOT) places users in a virtual mechanized combat environment in which they control a mechanical avatar in a one vs. one battle arena. The purpose behind using this virtual gaming environment is due to the steep learning curve that will task the user with having to learn the game and its complex control schemes, instead of just trying to a complete a simpler task. Using two hand operated joysticks, users operate their mechanical avatar’s basic movement, aerial maneuvering, and weapon based attacks (For more in depth explanation of the VOOT controllers and specific functional-commands please refer to Table 1).

The controllers specific to the design of the study were the Xbox 360 standard gaming controller and the Hori Twin-Stick EX (Figure 2). The standard Xbox controller serves as the more generic interface, as this control comes prepackaged with every Xbox 360 gaming console.
with a purposeful design to be usable in any Xbox gaming environment. Using two thumb operated joysticks with coordinated action commands (Figure 2), the user is able to navigate within the gaming environment. The Hori produced Twin-Stick peripheral was selected to assess the potential task-relevant aspects of control use in VE, for the design and implementation of such an interface was purposefully tailored for VOOT. Grasping the twin sticks with both hands, the user operates their virtual avatar through coordinated wrist movements and function-specific action commands (Figure 2). The optimal specificity of the Twin-Stick design stems from the fact that the original arcade cabinet (Cyber Troopers: Virtual-On; 1995) implemented the same peripheral to be used in this study. Thus this Twin-Stick version for the Xbox 360 gaming console accurately replicates the original control experience. It should also be noted that the action-command layouts for VOOT were also developed with the twin-stick design as its interface foundation (Table 1).

Though the Xbox controller design was not implemented until nearly a decade after the original Virtual-On arcade release, the generic and flexible design of the Xbox controller does allow for an accurate mapping of the Twin-Stick interface. The differences found between the two interfaces is more based on size, weight, and the specific effectors used to operate both controllers, more than it is a difference in controller functionality. The similarities and differences of the two controllers allows this study to examine how the action-capabilities provided by the two interfaces influence task-relevant learning and development of coordinated control strategies within the virtual gaming environment. Using an interface that was designed for the gaming environment, and one that serves a generic purpose for any gaming format, the design of this study looks to examine how learning through interacting with these interfaces reflects performance within the gaming environment, and how user developed coordinated control strategies translate from one interface to the other.

In regards to the idea of task-relevance, this study looks to examine how the implementation of learned task relevant or irrelevant control strategies impacts the development of coordinated strategies and if these strategies will positively or negatively transfer to the opposing controller. To examine this question a two group controller order was implemented to assess how the order in which a controller is given to the user effects the development and use of
coordinated control strategies within the gaming environment.

**Present Study**

The purpose of the present study is to further examine the enactive human-controller system, and subsequent consequences that occur through the use of the controller in virtual environments; specifically, through the understanding of how behavioral (postural and coordination) constraints of the controller influence the perception and action of motor affordances utilized by the user and the resulting goal-oriented outcomes (performance). Focusing on the quantification of behavior allows us to examine the patterns of control and coordination that develop and persist overtime given the specifications of the controller in use.

To this extent this study aims to test the hypothesis that a controller-interface that perceptually (Type-Alpha) and physically (Type-Beta) constrains the user to the appropriate-task specific action capabilities dictated by the perceptual information of the virtual environment, will allow the user to adapt proficient behavioral control strategies that enhance the performance necessary to reach the specified goal state. Controls that more accurately fit the capabilities of the virtual environment will result in behavioral patterns that are quantified as adaptive, and beneficial towards reaching the goal state. In regards to performance, these appropriate behavioral control strategies should produce an increase in performance within the environment. The degree to which the user can sufficiently incorporate and employ these strategies depends on how well their intended behaviors translate through each controller-interface. Though the user will interact with both controllers, it is possible that the behavioral control strategies that develop through the use of the initial controller will influence behavioral and in-game learning that also translates when switched to the second device.

To discover how distinct action-capabilities influence the successful coupling to the affordances of the environment, this study will manipulate how users interact in a virtual environment with a set of novel control schemes. The controllers that serve as the interfaces for this study are very similar in function, but differ in properties of size, weight, and required effectors (thumbs vs. wrists) used to operate the given interface (Figure 2). For further understanding of the nature of the controller mechanics please refer to controller schematics (Table 1) found in the method section, which describes the necessary functions to navigate in the virtual environment. It should be noted from controller schematics that coordination is an
essential tool which must be utilized to meet the given tasks of the environment.

To quantify the control schemes for this study, we chose a series of synchronized non-linear analytical techniques. These measures enable a more detailed examination of how users are behaving within the virtual environment, which cannot be captured by more traditional measures of magnitude or spread. Traditional measures such as, velocity and variability, can capture the extent of a specific behavior (how much) the user is exhibiting overtime. But cannot depict what it is that the user is doing or the manner in which these actions are being performed. Though quantitative in nature, much like that of more traditional measures, these non-linear measures allow for the characterization of what the user is doing and how they are doing it. In short the changes in the quantitative aspect of the measures represent qualitative changes in behavior. Given the nature of the task in this study the following measures were employed as they can provide measures of the coordination of the body-segments used to operate the controllers:

**Coherence.** This measure captures the similarity of frequencies between two waveforms, in this case the motion of the arms and hands. To this extent the coherence measure examines how much the movement of one joint “locks” with the movement of another joint overtime, higher values indicating an increase in time-locked behavior of the coordinated joints. The coherence measure is correlation measure that works in absolute values, a value of one representing perfect synchronicity between coordinated segments, zero representing no relation between the two segments. Given the dynamic nature of the task, in which the coordinated segments must at times be increasingly correlated and at other times less correlated (see Table 1), it is expected that mean values derived from this measure fall within middle of the coherence’s specified range, regardless of the controller due to similarities in function between the two interfaces (Strang, Funke, Knott & Warm, 2011). However, over time there should be changes in this value that can be used to determine the type of behavior that was occurring at that moment.

**Cross-Fuzzy Entropy.** This index measures the spatial-temporal similarity of the coordinated segments. This measure allows for the determination of how stable a given coordination strategy is. Using this technique it is possible to assess how much of a given segment’s movements can be predicted from what the opposing coordinated segment is doing. Lower values (approaching zero) suggest that the coordinated segments are in synchrony, and
somewhat dependent over time. Higher values derived represent coordinated structures that are increasingly independent over time, in essence becoming less synchronous; specifically with an entropy value approaching three typically indicating random or independent movements (Xie, Zheng, & Chen, 2010).

**Cross-Correlation.** The cross-correlation is a correlation that accounts for time lag, while determining how correlated in space the two coordinated segments are to one another. In relation to the controllers used for this study, the cross-correlation examines the extent in which the user is using both sticks in the same (coordinated) manner and how this changes overtime. Unlike the absolute correlation coefficient of the coherence measure, cross-correlation produces values from -1 to 1, much like more traditional correlative measures. Referring to the controller schematic layout (Table 1) found within the method section, the dynamic nature of the task will require the user to display both higher (ex. Chasing opponent) and lower (ex. Evading fire through flight) correlated values at times that appropriately match the response of the task. Because of this it is assumed that overtime the dynamic shifts in derived correlative values should to a relative degree match the task-specified actions in the environment for successful performance (Stergiou, 2005).

It is important to keep in mind that these derived values do not represent the optimal behavioral value necessary to be proficient in the given task; merely these values represent what the user is doing at that given time. Because of this, the intended use of these measures is to better determine what values, and thus behavioral structures are relevant to the task. Given the nature of these measures it is predicted that each controller will yield unique profiles of synchronicity that will allows us to better quantify user behavior and the specific relationship to VE performance.

**Method**

**Participants**

Fifteen undergraduate students ranging in age from 18 to 24 years were recruited for this study-- six participants were male and nine female. All participants had normal or corrected-to-normal vision and reported to be in good health. Thirty-three percent (33%) indicated that they had no prior experience interacting in a virtual gaming environment (or at least of this caliber; i.e. angry birds). The sixty-six percent (66%) of students indicated previous experience in a
virtual gaming environment, with 66% of this group specifically indicating prior experience with the Xbox 360 gaming console and controller, or similar gaming system (i.e. Playstation 3). Participants received course credit for their time in this study. Participants were also instructed to refrain from eating two hours prior to their scheduled time (this was verified at the beginning of the session). Regardless of any disqualification that occurs during the study the participant would receive full credit. Participants were treated in accordance with the American Psychological Association (APA) ethical standards at all times (APA, 1992) and the research protocol was approved by the university’s institutional review board.

Materials

**Display.** A Sharp XR-32X-L LCD projector was used to display the VE. The approximate physical image dimensions were 2.2 m high x 2.85 m wide and 2.8 m diagonal yielding a visual angle of 25 degrees diagonal from a distance of 6 m.

**Game console and software.** A Microsoft Xbox 360 (Microsoft, Inc) gaming system was used to generate the virtual environmental stimuli for the study. A 3rd-person (perspective) 3D (dimensional) mechanized combat game (Virtual-On; Sega, Inc.) was used as the virtual stimuli for this study. The training mode option was used for the control and experimental trials (figure: maybe). The Space Port level of the game was selected due the option of inverting parts of the environment; allowing experimental control of the combat arena, while instilling a sense of novelty to the participants. During experimental trials, computer controlled A.I., health, and damage output were set to their default (normal) settings, to ensure that participants would be able to interact with the game with a balanced difficulty for the 5-min data collection period.

**Controllers.** Two controllers were employed to test the study’s hypothesis. A standard Microsoft Xbox 360 controller was used to control movement within the virtual environment through dual thumb-stick manipulation A Hori Twin-Stick EX controller (HORI Inc., Japan) gives the user control of two operational joysticks that are used to control the mechanical avatar. Due to the size of the device, user’s actions required more hand-forearm movements; buttons for the weapons systems and combat capabilities are positioned in the anterior and crown of each stick allowing easy access through natural grip. Please see Table 1 for more detailed description of controller functions and Figure 1 for controller schematics.
Motion Tracker. A magnetic tracking system (Flock of Birds; Ascension, Inc.) was used to track postural motion and motor coordination. This system detects motion in six degrees of freedom (3 axes of translation and 3 of rotation). A centrally located emitter creates a low-intensity magnetic field of known strength, extent, and orientation. Receivers (“birds”) move within this field. The system detects the position and orientation of each bird to an accuracy of 1mm. Six ‘birds’ were utilized: one on the head, one on the thoracic area of the spine, one on each wrist, and for the user’s interacting with the traditional controller (Xbox 360 controller) one on each thumb. Data from the ‘birds’ was sampled at a rate of 40Hz. Motion data was collected with Motion Monitor Version 8 (Innovative Sports, Inc., Chicago, IL) software.

Procedure

Prior to the start of the experiment participants were informed of the nature of the study. Before they could comply with the tasks of this study they were required to read through and sign an informed consent form. In addition to this process, participants were asked to complete a general demographic sheet indicating age, gender, height, weight, and more detailed information regarding previous interactions with virtual environments. To ensure the participant were able to comply with the constraints required of the experimental task in an efficient and safe manner; two forms of balance tests were performed: First, a standard field sobriety test where the participant is required to walk heel-toe in a straight line using a line marked in red tape to guide their actions and second, a balance check required participants to stand on one foot (participant’s preference) with their eyes closed for duration of 30 seconds. Adequate success in these tests was required to further progress toward the completion of the study. All participants were able to successfully complete both balance tasks and moved onto the second phase of the study.

Sensors were attached to the participants’ head; lower spine (T12), right and left wrists, and right and left thumb using Velcro belts/bands. Participants sat on a stool (which did not provide back support) holding the game controller in their hand or stable platform (for the Twin-Stick controller). The purpose of the setup was designed to mimic more typical playing conditions while requiring some form of active postural regulation. A total of four trials were administered in each session. Due to the nature of the study, participants participated in two different sessions transitioning from one controller to the other. The order in which participants received the controllers during each session was counter-balanced (Twin-Stick to Xbox; Xbox to
Twin-Stick) to control for any behavioral effects attributed by the controller. The first trial (control) was used to ensure participants had an adequate and functional understanding of the control schemes and basic actions necessary to interact in the environment, through a hands-on demonstration by the experimenter. After the instructional demonstration, participants were instructed to complete a list of commands that covered the basic tools for piloting their character (movement, flight, and weapon systems). Once the lists of commands were completed participants were allowed 4 minutes to practice before the start of the experimental trials.

The next three trials were the experimental trials; each lasting 5 min in duration. During each trial the computer controlled opponent was activated, and the participants were required to engage the enemy in a best of nine, using any technique or strategy to try and defeat the computer controlled opponent. Between each round the experimenter recorded the performance of the participant via a win/loss ratio. Participants who had completed both sessions were debriefed before leaving. All participant data collected from this study were stored on a computer and analyzed at the completion of the study.

**Results & Discussion**

For each participant, performance data was collected for the behavioral task. The win/loss score (number of defeats or defeated CPU opponents) for each of the participant’s five-minute trials, for both the Xbox and Twin Stick controllers were collected and converted into a percentile score. Participants ratio scores were then compared across the two controller interfaces (Xbox vs. TWS), and the order in which the participant interacted with these interfaces (TWS-Xbox or Xbox-TWS). For the current analysis the differences between performance via the two interfaces and the order in which they occurred were examined using a 2x2x6 mixed subjects design with a between subject factor of order (Controller x Order x Trials; with Order being a between factor).

A series of 2 x 2 x 9 mixed subject designs were employed (Controller x Order x Time; with Order being a between factor), to assess the angular-postural data (Heading & Pitch) of the thumb ad wrist joints, using the C-FuzzyEn as the dependent variable for each series. The C-FuzzyEn analysis enables the measurement of synchronous patterns that are emitted between two distinct waveforms (i.e. signals emitted from thumbs and/or wrists). This non-linear measure captures the spatial-temporal structure of the given wavelengths, examining the complexity of these synchronous patterns overtime. (Xie, Zheng, & Chen, 2010). The data collected over the
course of 10 minutes was then chopped into two minute windows where the first, middle, and last time segments for each trial were selected for analysis. Segments were not averaged over trial, as the goal was to examine the development of behavioral control strategies. (Bonnet et al., 2006).

The coherence time-series analysis examines the frequency in which two synchronous signals are moving through time (Strang, Funke, Knott & Warm, 2011). High values of coherence indicate higher signal frequency. A structural difference in the frequency rate in which both joints are moving to operate both controllers, may provide insight into the difference found in the performance analysis. To assess this hypothesis a series of 2 (controller) x 2 (order) x 9 (time) mixed subjects design were performed to analyze the coherence dependent variable for both the heading and pitch axes.

Using the Cross-Correlation (CC) non-linear analytical technique, the spatial coordination of the thumb and the wrist segments used to operate the Xbox and Twin-Stick controllers respectively were examined. A series of 2 (controller) x 2 (order) x 9 (time) mixed designs were employed, using the CC time-series analyses as the dependent variables.

**Performance**

**Virtual Environment Performance.** Participants win–ratio score was selected to be used as the primary data for this analysis. At first, we conducted a 2x2x6 mixed subject design with a between subject factor of order (controller x order x trials); in order to assess any effects that may exist in performance between the two controllers over the course of the tree trials for each interface. A main effect of controller order was found to be of significance; $F(1, 13) = 6.702, p = .022$. When presented with the Twin-Stick controller first, participants performed better overall than individuals who received the Xbox controller first (Table 2). No other effects reached significance.

Although the analysis failed to reveal significant differences in performance across trials or an interaction between controller order and trials, the pattern of data suggests a non-trivial difference exists.

Specifically, the descriptive data (Table 2) revealed that individuals who were initially given the Xbox controller, performed better in their first three trials than those who utilized the Twin-Stick first. Looking at the last trials of both the Twin-Stick and the Xbox controllers, we
find that the level of progress for those who switched to the Xbox controller continued to improve, while those who switched to the Twin-Stick controller displayed a decrement initially and then began to improve over the course of three trials. While those who utilized Twin-Stick controller second did increase their performance at the end of trial six, the fact that the performance of their first two trials with that controller exhibited weak and inconsistent outcomes when compared with their previous performance suggests some learning or behavioral control strategy disruption between the two controllers. This disruption does not seem to be experienced when utilizing the Twin-Stick controller first.

The analysis of the performance data indicates the possibility that there are no significant differences between the performances of the two controllers, such that one controller is not necessarily designed better than the other. In addition for the sake of arguing, though the Twin-Stick was designed for the virtual environment it may not be optimal for performance. However, how the user interacts and learns while using each controller may significantly alter how they perform with the other device. We suggest two potential reasons for why this effect may exist: 1) The way in which the controls are used by the participants is structurally and behaviorally different, such that the way in which the user learns one controller is incompatible with the other interface; 2) The task (ir)relevant design of both controllers effects how individuals action-capabilities develop overtime and transfer to the other controller.

**Postural Motion Plots**

In an attempt to understand how postural motion and subsequently behavioral control is being regulated by the novel capabilities of the VE and the applicable action-capabilities provided by the two controller interfaces, it is important to visualize the actual controller behaviors taking place while interacting with the virtual environment. Visualizing these actions allows us to see what (if any) changes are occurring and how these changes are supported by the subsequent quantitative analyses. The first step of this process was to construct plots that illustrate the controller behaviors the participants were exhibiting in the gaming environment. A state space plot was created to depict motion along two axes (pitch and heading). It should be noted that the state space plots were intended to be representative of the data generated in this study, but were generated from only two participants (one to represent participants who received Twin-Stick to Xbox and one to represent participants who received Xbox to Twin-Stick.) The
state space plot was divided into four quadrants: A (Order 1 Twin-Stick), B (Order 1 Xbox), C (Order 2 Xbox), and D (Order 2 Twin-Stick).

**State Space Plots (Figure 3).** In comparing Twin-Stick to Xbox (A, B) and Xbox to Twin-Stick (C, D) we observed increased variability over the progression of trials, as well as increased variability between controllers for the selected participant from the Twin-Stick to Xbox controller condition. This is in contrast to the decrease in variability over controllers seen in the participant from the Xbox to Twin-Stick controller condition. This pattern of motion from the Xbox to Twin-Stick participant may represent a reduced ability to access the appropriate task-relevant information necessary to stem appropriate behavioral strategies necessary for adequate performance.

When comparing the controller conditions with increased variability (A, B, & C) with the decreased variability condition (D), it appears that the variability in their behavioral patterns is needed for the purposes of learning, adapting, and overall performance. Looking at the decrease in variability (D) of the Twin-Stick depicts a rigid control strategy where the commands guided by the pitch axes begin to fade, and overall heading axes commands decrease in stability (*Author’s Note: Many individuals in this group displayed constant commands of stationary flight, which resonate with the variability in only the heading axis). This suggests that user switched to a more simplistic control strategy regardless of the dynamic variability of the task. In contrast, examining the control strategies of the state spaces (A,B, & C) demonstrated the possibility that the increase in variability expresses user control strategies involving various commands in both axes that are flexible and adapt to the dynamics of the environment, this too is consistent with the performance data (Table 1). While the decrease in variability and visually rigid patterns displayed (D) suggest that the criteria for successful control are not supported; this is confirmed by the performance data (Table 1), where Twin-Stick performance decreased after transitioning from the Xbox controller (Hendriks, Spoor, Jong & Goossens, 2006; Littman, Otten, & Smart, 2010; Riccio & Stofregen, 1991; Smart, Stoffregen, & Bardy, 2002; Smart, Otten, & Stoffregen, 2007; Smart, et al., 1998; Stroffregen, et al., 2002; Stoffregen & Smart, 1998).

**Issue of Design: Controller Scale -Cross-Fuzzy Entropy Analysis**

While investigating the differences between the two controllers, it was important to
determine that both controllers, though physically different functioned in the same manner. To ensure that participant’s were behaviorally interacting with both controllers in the same manner (given the fact that they differ based on thumb vs. wrist manipulation), a non-linear analytical technique called the Cross-Fuzzy Entropy (C-FuzzyEn) was employed.

**Cross Fuzzy Entropy: Heading- Axis**

The factorial ANOVA for the heading-axis found a significant main effect of Controller, $F(1, 14) = 73.510 \; p > .001$. The C-FuzzyEn value of the Xbox controller ($M = .179, \ SE = .012$) was significantly higher than that of the Twin-Stick value ($M = .089, \ SE = .014$). The increase in C-FuzzyEn indicates that participants were more structurally complex and independent between coordinated joints overtime with the Xbox controller than when using the Twin-Stick controller (Figure 4). Given that the Xbox controller allows more flexibility (thumb movement) than the Twin-Stick (wrist), the difference in C-FuzzyEn values seems to confirm such an assumption. Though the Xbox was found to be more complex these values did not exceed limit in which structural patterns of movement are seen as chaotic (Xie, Zheng, & Chen, 2010).

There was a marginal effect of Time (Beginning, Middle & End of each trial), $F(1, 7) = 2.791, \ p = .097$. The trend of time suggests that structural complexity of the C-FuzzyEn index changes as time progresses through each trial and in comparison to all three trials overall. This would indicate that the nature of the task changes the complexity of the behavioral pattern of the participant. No other effects were found.

**Cross Fuzzy Entropy: Pitch-Axis**

There were no effects found in the factorial ANOVA for the pitch-axis of the C-FuzzyEn analysis. Though the analysis depicted in Figure 2 found the C-FuzzyEn values of the Xbox controller to be higher than that of the Twin Stick over the course of all time segments. The increase in variability between both controllers was determined to be too large to be significant. Once again trends for both the Xbox and Twin-Stick controller were very similar in pattern and structure, differing only in magnitude. This would suggest both controllers are being operated in the same manner, with slight differences due to the nature of how each controller is manipulated. It can also be inferred that the reason that no effect was found in the pitch-axis due to the reliance of heading oriented commands (ex. Flight), it is possible that Xbox users tend to neglect pitch related commands. It is also possible that these individuals merely favored heading-
oriented commands due to the natural lateral flexibility of the thumbs, a possible maladaptive behavior due to the design of the Xbox controller.

**Xbox-TwinStick Cross Fuzzy Entropy Discussion:**

Figure 4 shows that though the controllers differed in their C-FuzzyEn values, with that said, the patterns of their C-FuzzyEn values are structurally very similar overtime. It is suggested that the difference in C-Fuzzy values is in accordance with the nature of how each controller is manipulated by the user, such that the Xbox controller gives the use more flexibility via thumbs than that of the wrist joints used to operate the Twin-Stick. The freedom and flexibility of movement may indicate behaviors that may be less accurate and precise in in-game commands in comparison to the twin-stick. Given the more constraining nature of the Twin-Stick it is arguable that the requirement of more purposeful action-oriented control is demanded, thus reducing the ability to lose control and coordination overtime an important dichotomy in relation to the Xbox controller. Though not measured in this study there may be benefit in documenting in-game actions demonstrated by the user to understand if structural stability is indicative of differentiated play styles.

Although their values do differ, the structural patterns of the two controllers were fairly similar suggesting that both controllers, though operated with two distinct joints, are used in the same manner. This would indicate that both controllers function very similar, such that the Xbox and Twin-Stick are merely differ in the fine versus gross motor movements required to operate. Of course the difference in the specificity of motor activity may provide indications of how the user learns given these two controllers.

**Frequency of Behavioral Movement: Coherence Analysis**

A Coherence (Coh) non-linear analytical technique was employed to determine any temporal-structure (time-locked frequencies) differences between the two devices.

A significant main effect was found for controller for the Heading, $F (1, 13) = 8.710, p = .011$ (Xbox $M = .249$, SE $= .012$; Twin-Stick $M = .212$, SE $= .009$); and Pitch axes, $F (1, 13) = 20.794, p = .001$ (Xbox $M = .291$, SE $= .011$; Twin-Stick $M = .207$, SE $= .012$). Similar to the results found in the analysis of the C-FuzzyEn, the Xbox controller was found to have a higher synchronous frequency rate (higher coherence values) than that of the Twin-Stick. The increase in Xbox coherence values suggests that the coordinated joints used to manipulate the Xbox
controller are more frequently locked in their movement’s overtime in comparison to the Twin-Stick controller. We presume that this effect exists due to the flexibility of the thumbs and their close proximity to one another. What this analysis cannot tell us is if these frequent time-locked behaviors result in more synchronized coordination, directionality or controller command behaviors of the Xbox controller, merely their synchronized movement overtime. As Figure 5 depicts, though the difference in coherence were significant, the size and structure of the coherence trends over the course of the entire study were fairly similar across controllers, and controller order. As predicted regardless of controller or order these values fell within the middle of the coherence’s specified range due to similarities in the function between the interfaces (Strang, Funke, Knott & Warm, 2011).

**Coherence Discussion**

The differences in frequency may indicate the more synchronized behavioral patterns of the thumbs in comparison to the wrist, especially as the thumb is a much more flexible and utilized joint. Although this difference exists, the distinct similarities in the trends presented in Figure 3, do not suggest that these frequency differences allow the participants controller oriented behavior to differentiate from one controller to another, nor do there seem to be any behavioral obstacles that may have impeded participant performance on a certain controller.

It is important to note that though the structural patterns presented in Figure 5 are very similar across controller order. There are noticeable structural differences between the two orders. Similar, to the patterns seen in the C-FuzzyEn, There seems to be a behavioral influence of the initial controller that helps shape the behavioral control of the following controller. As we can see the structural trends between controllers in the same controller order are also fairly similar. This may potentially shed light on how the consequences of using a particular controller develop certain behavioral strategies to that carry over for instance the natural reliance of more heading-oriented commands due to the use of thumbs may result in an adapted behavioral strategy that is employed by the user in the future. This supports the previous notion that some type of behavioral control carry over exists as participant’s transition from the two controllers. The question is whether is phenomenon has an effect on performance.

**Examining the Structural Coordination of Movement: Cross-Correlation Analysis**

Based on the analysis of the performance data and C-FuzzyEn, the designs of the two
controllers does not appear to present any initial performance differences (although synchronicity decreases when operating the Xbox controller); such that the Twin-Stick game controller being solely designed for the virtual environment *Virtual-On* does not naturally lead to better performance. Though as seen in the significant 2-way interaction of Controller * Controller Order of the performance factorial ANOVA, the order in which the controllers are received significantly affected the performance outcome of the follow-up day. This result suggests that the potential task relevant design aspects of either controller plays an important role in the participants’ performance and overall learning over the course of the study. We also noticed a similar trend in the C-FuzzyEn and Coherence analysis, though those analyses were not used to assess performance, but to ensure that the two controllers in question functioned in the same manner behaviorally for this study. Using the Cross-Correlation (CC) non-linear analytical technique, the temporal structural coordination of the coordinated segments for the Xbox and Twin-Stick controllers were examined.

The 2 x 2 x 9 mixed design for the cross-correlation heading axis found there to be a main effect of controller approached significance, $F(1, 13) = 3.998, p = .067$. The participants’ using the Twin-Stick controller were more higher or lower (depending on the current behavioral task, see Figure 6) in their wrist movements, than that of the thumbs when using Xbox controller. The analysis also found a significant 2-way interaction of controller * controller order, $F (1, 13) = 8.397, p = .012$. The significance of this interaction indicates that the level of coordination for each controller differed depending on the order in which the controllers were given. No other significant effects were found. There was no significance found in the pitch axis. Figure 6 presents the cross-correlation values of the Twin-Stick and Xbox controllers. When assessing the order in which the controllers were received, we see in Twin-Stick to Xbox, the Twin-Stick was more correlated than the Xbox controller. This effect diminishes when assessing Xbox-Twin-Stick, where the both controllers share similar cross-correlation values. One of the more notable findings in this figure is the distinct difference in coordination between the Twin-Sticks in order 1 and 2. Looking at the pitch axis the activity of users using the Twin-Stick second barely shows any activity overtime supporting the claim of possible over reliance of heading-oriented commands previously exhibited when utilizing the Xbox controller. Although the coordination values between the Xbox orders are different, the difference is very slight. What should be noted
between the two Xbox control-groups are the relatively high correlation values in the pitch-axis of users who utilized the Xbox controller first; indicating the use of more directionally synchronized commands (ex. moving forward). This suggests that there seems to be a behavioral control strategy effect that carries over from one controller to another. This seems to be supported by the structural patterns of the trends presented in Figure 6. Even though there were no effects found in the pitch-axis factorial ANOVA, we can see that in each order the trends are very similar between both controllers.

It is also important to understand the relation of the correlation analysis to the user activity in the environment. Based on the commands the user initiates with both sticks of the controller (wrist or thumb operated) the user maybe become synchronized (ex. Command mech to walk forward) or not synchronized (ex. Jumping- requires both sticks to be pulled to opposing sides). Examining Figure 6 panel A & C, we see this polarizing switch between being higher or lower in coordination values using the Twin-Stick. This shift shows that the users of the Twin-Stick order 1 are very coordinated in their controller commands. In regards to the mechanisms of Virtual-On’s controller layout, the pitch-axis of TwinStick-Xbox indicates important coordinated techniques 1) User’s were successful in synchronizing similar or opposing directional commands 2) more importantly these user’s were able to switch from strategies that require both sticks moving simultaneous to the movement of one stick while the other remains in its idle position.

For example, the dash commands (Table 1) do not require both sticks to be positioned in the same direction. A useful technique that can be employed for more accuracy and precision for certain command sequences such as flight to air-dash to land; is to first coordinate the pulling both sticks in opposite directions (initiating flight), allow one of the sticks to return to the neutral position and initiate the dash command with the other control, initiate turbo button to disengage air-dash, and reengage idle stick moving both controls inward to land. Although the Xbox controller in this condition does not depict as strong as the Twin-Stick pattern, it can be seen that the Xbox controller seems to follow in the Twin-Sticks developed strategy, specifically going from higher to lower correlative values overtime, suggesting the time of actions the user was initiating as that moment. Once again this suggests that initial control strategy developed carries the information to aid (or inhibit; see Figure 6 B &D) control strategy with another controller interface. With these findings the higher coherence values of the group who initially used the
Xbox controller coordinated frequency behavioral movements were so time-locked that these individuals did not exhibit the ability to initiate simultaneous to isolated control switching (Figure 5).

**Cross-Correlation Discussion**

When relating this to the performance data, we found that overall the Twin-Stick and Xbox controllers performed fairly similar in regards to win ratio on the initial day of testing. As the two ordered groups switched controllers the following day, we find that performance did differ, with Twin-Stick to Xbox performing better than Xbox to Twin-Stick. Examining the trends in Figure 6, it would seem that the behavioral controls strategy of the initial controller influences control strategy that the participant employs when switching controllers. In relation with the performance data, evidence suggests that the Xbox control strategy seems to negatively affect the Twin-Stick performance and the control strategy used to operate that controller. Though the level of correlated coordination of the Xbox controller did drop in comparison to Twin-Stick in order 1, we found that the cross-correlation values were similar to the initial Xbox correlation values in order 2. This suggests that the Twin-Stick control strategy does not positively nor negatively influence performance, but modifies the control strategy adapted for the Xbox controller, such as the simultaneous to isolated control technique described previously.

The combination of performance and the cross-correlation analysis may indicate that the design of the controller that better encapsulates the task relevant aspects of the virtual environment may provide the user with the appropriate options to be successful in the virtual environment. The Twin-Stick being the control device designed for the virtual game environment *Virtual-On*, was designed to constrain the user to the actions that are appropriate to perform in the virtual environment. With its twin stick design, and large control base, the user is constrained to the afforded options that the environment requires. Although the Xbox controller is designed to efficiently perform in the environment. The Xbox controller is a universal controller designed to allow the user to perform in a diverse array of environments. Because of these diverse and flexible options, it may potentially teach the user inappropriate behavioral strategies that do not positively carry over to other control devices. This would explain the similar structural patterns in the presented figure 4, as the control strategies learned by the task-relevant designed Twin-Stick allows the user to appropriately adjust to take those strategies best
fit to perform successfully in the virtual environment. These strategies are then carried over to other controllers that might not be best suited to perform in the intended environment.

Taking the analysis of the of both the C-FuzzyEn and Coherence measures, supports this notion of task-relevant control strategy influence. The analysis of these measures determined that the nature of the task was not structurally different between controllers, providing evidence that both controllers were operated by the users in the same manner allowing for the examination between information provided by the wrists (Twin-Stick) and thumbs (Xbox) to be furthered investigated. As seen in both the C-FuzzyEn and Coherence measures the structural patterns of the Twin-Stick and Xbox were very similar, while the Xbox amplitudes were significantly higher. We previously suggested that the reason why the values were found to be higher than that of the Twin-Stick was due to the thumb manipulation required for the Xbox controller. The thumbs allow for more flexibility, thus giving the user more options and fewer constraints on actions possible.

Though the controller provides the user with efficient control, it may also develop inappropriate habits that are irrelevant to the given task. We see in the CC analysis of Xbox to Twin-Stick, that the coordinated thumbs are fairly correlated to some degree with one another (Figure 6 panel B, D). Yet, the controls strategy that is devised due to the coordination of the Xbox controller is not appropriate for the Twin-Stick, whose wrist manipulated controller seemingly requires more control and coordination to provide efficient performance. Given this evidence, it can be assumed that the information the thumbs provide the user in the virtual environment, provides too many options that though domain specific, do not allow for the user to maintain or progress the level of performance across controllers. Based on the evidence provided, we may also be observing the differences that emerge through fine versus gross motor activity. Though the thumbs are flexible the analyses found Xbox control user’s to initiate in more lateral (heading-oriented) commands, as the thumbs naturally favor these types of orientations with or without a controller. While the wrists may not be as favorably locked to commands of a certain orientation, thus the exploratory and consequential behavioral learning may be more expansive, even given the highly constraining Twin-Stick device. This is a question that should be further addressed in the future.
Conclusions

The current study sought to understand the nature and mechanisms of user control by focusing on the motor action and coordinated aspects of the user’s interactions within the selected virtual environment. To examine this issue, we selected two distinct controllers to better understand the behavioral responses to the degree of control in a virtual environment. With these two distinct interfaces, the purpose of this study sought to examine the design, constraints, and action capabilities of each controller; and how these properties influence behavioral control strategies and performance.

Overall, it cannot be concluded that there is a distinct difference in performance between the two controllers. The analysis of behavioral and performance data, indicates that the capabilities of these devices have a significant effect on learning and behavioral control and coordination, which created the distinct performance trends observed when transitioning between the two controller interfaces. In line with the findings of Walker et al. (2007), the Twin-Stick controller, whose design was crafted solely to provide the necessary task-relevant actions to operate in the virtual environment, was found to establish behavioral control patterns that related to successful performance trends in comparison to individuals who initially utilized the Xbox controller. As examined in the initial performance data, this was not due to the fact that the Xbox controller did not provide the necessary action-capabilities to be successful in the virtual environment, as these individuals were initially more successful. As the two controller order groups transitioned from their respective controller to the other, the analysis found a significant decrease in performance as individuals moved from the Xbox to the Twin-Stick controller. The effect suggests that the enabling of certain action-capabilities provided by the Xbox controller establishes inappropriate behavioral control strategies that are not employed by the Twin-Stick when utilized first.

Based on the design of the Xbox controller, it would appear that the flexible and universal design of the device presents the users with motor actions and behavioral information that is not necessarily relevant to given task though it was found suitable to accomplish such a task (Kay, 1998). We suggest that given this evidence the two controllers’ capabilities differ not in task optimization, but in behavioral optimization. When required to transition from the Xbox
to the Twin-Stick interface, such task-irrelevant properties and information hinder the adaptation and learning of the user. To the extent that performance is reduced.

The flexibility of potential action-capabilities of the Xbox controller may reflect the nature of optimal control in which the user is given access to specifically, error, stability, and control activity. In regards to error, the flexibility of the Xbox controller reduces the accuracy and precision of purposeful action-commands, which is more constrained in the Twin-Stick Device. Evidence provided from the Cross-Fuzzy Entropy (Figure 4) measure found the Xbox controller to display more variability in coordinated joint stability overtime, suggesting that as time passes the increase loss of synchronicity may indicate the loss in accuracy and controller command error. The design of the Twin-Stick prompts the manipulation of certain actions that are more constrained to the positions that are ideal for those commands. In such a complex task where the difference between flying over an enemy projectile versus mistakenly turning in place is pivotal to in game success, the deterioration coordinated joint stability is an affordance that cannot be allotted.

Overall, the Xbox controller was found to be more behaviorally active (Control Activity) suggesting the flexibility and nature of the controller influences the user to be more active in their approach to the gaming environment, even though such activity may not be necessary and possibly disadvantageous. Not only did the synchronized structure of the coordinated joints for the Xbox controller break down as time progressed, we also found these actions to be more synchronized in regards to time and frequency. The combination of the Cross-Fuzzy Entropy and Coherence analysis indicate that these Xbox controller strategies display deteriorating structural coordinative patterns that are more tightly coupled together. This is to say that not only do these behaviors seem inappropriate they are also occurring at a much higher rate, a frequency that in consequence disrupts the user for learning more appropriate control methods.

Those who had experienced the Twin-Stick first, seemed to have avoided any “negative” behavioral control strategies due to the more strict motor constraints and action capabilities of the interface. These constraints imposed on the user by design were implemented to better match the tasks of the environment, tailoring the perceptual information and capable actions within the environment to those that most accurately reflect the given task. Based on the degree of consistency and gradual progression of the Twin-Stick to Xbox controller order group, it would
seem that the design of the Twin-Stick controller does not necessarily create the “best” performance environment. Rather its task-relevant design prompts an appropriate control strategy that successfully carries over and does not disrupt the users’ interaction with the Xbox controller. The stability in the users’ interactions allows the user to understand the mechanisms of the game and their physical actions overtime, thus becoming more adept in the later trials (Mcruer & Jex, 1967).

These implications are supported by the behavioral data captured using the set synchronous non-linear times series techniques (C-FuzzyEn, Coherence, Cross-Correlation). Results revealed from the analysis of these techniques provide insight on the control strategies being employed by each device. Examining the spatial and temporal patterns of the Twin-Stick and Xbox controller of both controller order groups, we can see that the presented waveforms differ in pattern and structure between the groups, but not between the controllers within each group (controller properties being accounted for the difference in amplitude and magnitude). This is in belief due to the behavioral control strategies that are developed over the course of the user’s time with their initial controller. As that control strategy develops, it seems to lock itself into a motor pattern that is used for the following controller device. Of course if this pattern is created from inappropriate control strategies or not for optimal user control, then the pattern seemingly conflicts with the design and function of the other control preventing the transfer of knowledge and skill to the other interface.

Further, it was observed that the structural coordination of the opposing joints used to operate each controller was found to be significantly different during the Cross-Correlation analysis. The analysis of the cross-correlation data reveals where the Xbox controllers presumed task-irrelevant properties begin to conflict with its Twin-Stick counterpart (see Figure 6). It is important to note the lack of difference between the Xbox controllers in both group orders, but the coordination between the Twin-Sticks. Users using the Twin-Stick after the Xbox controller saw a drop in coordination, and subsequently a drop in their performance data. This would support what has been previously stated in regards to the Twin-Stick’s influence on the Xbox controller; to the extent that there appears to be no significant effect positive or negative. The control strategy developed via the Twin-Stick may more accurately meet the requirements of the task and reflective the domains stated for optimal control.
It can be argued that the task-relevant design of the Twin-Stick teaches users the appropriate amount of motor control and coordination required; creating a stable base for another controller platform, such that the way information is conveyed to the user becomes “universal” in use. Such that the information conveyed is not specific to the controller itself, but the tasks and demands of the environment. The Xbox controller seems to play a pivotal role in dictating the behavior and control strategies employed Twin-Stick controller; one that merely forces its controller-specific motor actions onto another controller interface.

These findings suggest that there is not necessarily a controller that performs better than another (at least in an initial novel phase), but that the way in which the controller conveys perceptual and motor-control oriented information may be vital to user performance in virtual environments. The design of the controller should account for not only biomechanical factors, but behavioral and task relevant factors as well. Further examination of this issue is supported by these findings, specifically the potential learning differences that may result in the use of fine versus gross motor skills. This is not to take away from the findings of this study, but it is only responsible to look at other important factors that may contribute to certain effects.

Biomechanically these interfaces require two distinct joints that differ in motor specificity and detailed mechanical movements. These differences were highlighted by the Cross-Fuzzy Entropy and Coherence measures, as behaviorally the variability of the thumb joints may not have been sufficient in the acquisition of precise enactive knowledge used to navigate in this virtual environment. It is posited that a more longitudinal examination of fine versus gross motor skill coordination of an identical task be observed to further understand of biomechanical factors contribute to user skill and knowledge using these types of enactive interfaces. Many entities that employ the use of a controller are faced with the challenge of curbing negative behavioral effects, while tailoring to performance and an adequate user experience. In terms of measurement and data collection, techniques that can be used to understand behavior is important for the complete understanding of how the controller influences the user’s ability to successfully engage in the task of the virtual environment.
References


Table 1
Virtual-On Control Schematic Layout
*Note the “●” represents the central point of the controller. Arrows represent left and right sticks respectively.

<table>
<thead>
<tr>
<th>Controller-Functions</th>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Movement-Type</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Movement</td>
<td>↑●↑ ; ↓●↓</td>
<td>Operating both sticks in the same direction allows 8-way directional movement.</td>
</tr>
<tr>
<td></td>
<td>←●← ; →●→</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↖●↖ ; ↗●↗</td>
<td></td>
</tr>
<tr>
<td></td>
<td>↙●↙ ; ↘●↘</td>
<td></td>
</tr>
<tr>
<td>Rotation (Turning)</td>
<td>↓●↑ ( Rotate-Left)</td>
<td>Operating sticks in vertical-opposition initiates stationary re-direction.</td>
</tr>
<tr>
<td></td>
<td>↑●↓ ( Rotate-Right)</td>
<td></td>
</tr>
<tr>
<td>Dash (Turbo Boosters)</td>
<td>(While Moving + Any C)</td>
<td>Pressing 1 of the 2 turbo buttons (C; Figure 1), while moving initiates dash boost.</td>
</tr>
<tr>
<td>Dash Cancel</td>
<td>(During Dash + Any C)</td>
<td>Pressing either turbo button during dash cancels boosters.</td>
</tr>
<tr>
<td>Dash-Directional Change</td>
<td>(During Dash)</td>
<td>During dash, return both sticks to neutral position and select new direction with both sticks (*Must move in clock-wise or counter clock-wise motion).</td>
</tr>
<tr>
<td>Flight</td>
<td>←●→ (When Grounded)</td>
<td>Initiates Aerial maneuvering (*Can dash during flight time).</td>
</tr>
<tr>
<td>Landing</td>
<td>→●← (During Flight)</td>
<td>Cancels boosters while in flight.</td>
</tr>
<tr>
<td><strong>Attacking-Type</strong></td>
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<tr>
<td>Standard Attack</td>
<td>(D1; D2; D1+D2-Ground/Air)</td>
<td>Using any trigger (D; Figure 1) or both simultaneously activates specific trigger initiated weapon</td>
</tr>
<tr>
<td>Dash Attack</td>
<td>(While Dashing + Any D)</td>
<td>Fires trigger specific weapon while dashing.</td>
</tr>
<tr>
<td>Turbo Attack</td>
<td>(Simultaneous C + Any D)</td>
<td>Alters weapon properties when simultaneously operating turbo boost while firing.</td>
</tr>
<tr>
<td>Close Attack</td>
<td>(When Close + Any D)</td>
<td>Initiate melee combat while in close range.</td>
</tr>
<tr>
<td>Knock Down Attack</td>
<td>(During Knock Down; D2)</td>
<td>Delivers attack to a knocked down opponent.</td>
</tr>
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Table 2

*Means (S.E.) of Trial Win-Ration (N = 15).*

<table>
<thead>
<tr>
<th>Trials</th>
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<td>7</td>
<td>.368</td>
<td>.085</td>
<td>8</td>
</tr>
<tr>
<td>Trial 6</td>
<td>.576</td>
<td>.136</td>
<td>7</td>
<td>.621</td>
<td>.083</td>
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Figure 1. Hypothetical relationship between perceptual (alpha) and physical (beta) constraints in relation to possible behavioral outcomes.
Figure 2. The two selected controller interfaces for this study, Twin-Stick (Top) and Xbox (Bottom). On both controllers A & B represent the movement controls that operate the avatar 8-degrees of movement. C represents the turbo command that initiates the Dash function and alternate weapon options. D1 & 2 represents the weapon features of the avatar. *Note: controllers are not to scale.
Figure 3. Postural motion (Pitch & Yaw) of the coordinated wrists (Twin-Stick) & thumbs (Xbox) by controller order experimental conditions. Left column of each panel represents the left wrist/thumb; the right column represents the right wrist/thumb. The three rows (Top-Down) of each panel present the trial (3 for each controller) of the presented participants. A) Depicts the behavioral motion of Twin-Stick order 1 B) depicts behavioral motion of Xbox order 1 C) depicts behavioral motion of Xbox order 2 D) depicts behavioral motion of Twin-Stick order 2.
Figure 4. Mean wrist (TS)/ Thumb (XB) XFE over time for Pitch and Heading rotation.
Figure 5. Mean wrist (TS)/ Thumb (XB) Coh over time for Pitch and Heading rotation.
Figure 6. Mean wrist (TS)/ Thumb (XB) CC over time for Pitch and Heading rotation.