

The Effects of Simultaneous Control Noise in 2-Degree-of-Freedom Tasks on Optimal Control Strategies

by

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ABSTRACT

Understanding the stereotypical characteristics of human movement can better inform rehabilitation practices by providing a template of healthy and expected human motor control. Multiplicative noise is inherent in goal-directed movement, and plays an important role in computational motor control models to help support phenomena such as stereotypical kinematic profiles in time-constrained and unconstrained tasks. Most tasks are not carried out along an isolated degree-of-freedom (DOF), and modelling the contribution of noise can be difficult. In this work, we add a noise term proportional to the degree of simultaneity for multi-DOF tasks to approximate the contribution of system noise, and compare the simulation results against data from a 2-DOF experiment. With this approach, our model is able to explain previously observed motor phenomena including the presence of submovements in multi-DOF tasks, and the transition from simultaneous to sequential control of joints without the presence of visual feedback.

DEDICATION

For my mother, my eternal cheerleader.

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LIST OF ABBREVIATIONS

DOF	Degree of freedom
\mathbf{x}	State (e.g. $\mathbf{x} = [x \dot{x}]^1$)
A	Dynamical matrix
b	Control vector
\mathbf{u}	Control signal input
J	Cost
α	Value of completing task
β	Discount rate
\in	Is an element of
p	Time to complete task
λ	Motor command cost
τ	Inaccuracy cost
g	Desired final position
IQR	Interquartile Range
SD	Standard Deviation
NMES	Neuromuscular Electrical Stimulation

1 INTRODUCTION

Motivation

A myoelectric prosthesis is difficult to control, as it combines myoelectric signals (with inherent multiplicative noise) and reduced sensory feedback (Antfolk et al., 2013; Clancy, Bouchard, & Rancourt, 2001). This control scenario requires intensive mental concentration and considerable visual attention, which limits performance of myoelectric prostheses compared to able-bodied control and reduced acceptance rates compared to body-powered prostheses (Atkins, Heard, & Donovan, 1996). Clinically available myoelectric prostheses provide limited ability to control multiple degrees of freedom (DOFs) simultaneously, which in turn limits how closely prostheses movement mimics the coordinated multi-joint movements of intact limbs (Smith, Kuiken, & Hargrove, 2016). We are unable to provide better solutions for myoelectric control as we lack an adequate model of the human system to predict the movements observed during simultaneous control.

Objective

The objective of this work was to create and verify such a model to help provide better solutions for simultaneous control. An experiment was designed and conducted to validate the model's simulation results. The central hypothesis was that the degree of simultaneity is influenced by the level of simultaneous noise, and this was evaluated in simulation and experimentation. This objective was accomplished through the following specific aims:

- Specific Aim 1: To evaluate whether or not simultaneous multiplicative noise influences the optimal control strategies of 2-DOF human movement.

- Specific Aim 2: To test the findings of Aim 1 on humans to assess whether the simultaneous multiplicative noise in the control signal affects the optimal control strategies in a 2-DOF task.

2 LITERATURE REVIEW

Stereotypical human movement is well described by simple computational motor control models (Harris & Wolpert, 1998; Shadmehr & Mussa-Ivaldi, 2012). Some of these models adopt control policies to describe the behavioral choices that humans are known to make during a movement (Körding, 2007a; Todorov & Jordan, 2002). One objective of a control policy may be to minimize a cost function (Todorov, 2005). Some existing methods have incorporated multiplicative noise into their dynamics, affecting their optimal cost functions, which allows them to explain phenomena such as asymmetric velocity profiles (Harris & Wolpert, 1998; Shadmehr & Mussa-Ivaldi, 2012; Todorov & Jordan, 2002). However, they are unable to predict characteristics shown in more complex 2-DOF tasks, such as reaching to grasp a target, or operating 2 joints of a myoelectric prosthesis at the same time. Extending these existing optimal control models may allow us to solve these problems; and describe multi-DOF movement trajectories (Zhai & Milgram, 1998).

2.1 MULTIPLICATIVE NOISE

Consider a system that produces an output, $x(t)$. Additive noise does not depend on the state of the system. The additive noise, $n(t)$, is added to the true signal, $s(t)$, giving us $x(t)$.

$$x(t) = s(t) + n(t).$$

Systems that contain additive noise are easily solvable, and are appropriate in situations such as sensor noise. In certain cases, such as a Kalman filter, we can assume that additive noise is present. Additive noise is appropriate for many industrial applications, and has been a powerful tool for the purposes such as the Linear-Quadratic-Gaussian control problem (Todorov & Li, 2005).

In contrast to additive noise, multiplicative noise depends on the state of the system. Multiplicative noise can be represented as

$$x(t) = s(t) + s(t) n(t).$$

Multiplicative noise is required when modeling a human system, as it is inherent in biological systems (Harris & Wolpert, 1998). Some existing models have incorporated multiplicative noise into their dynamics, affecting their optimal cost functions, which allows them to explain phenomena such as asymmetric velocity profiles (Harris & Wolpert D M, 1998; Körding, 2007b; Shadmehr & Mussa-Ivaldi, 2012).

Multiplicative noise is present in most biological systems, as it arises from the underlying physiology of the motor-unit pool, i.e., the distribution of recruitment thresholds and the orderly recruitment of motor-units in a pool (Chhabra & Jacobs, 2006; Jones, Hamilton, & Wolpert, 2002). When comparing the variability of isometric force production from voluntary contractions to those elicited by neuromuscular electrical stimulation, it was concluded that the noise was not a result of peripheral neuromuscular noise (Figure 1). Multiplicative noise was found to be present in voluntary isometric contractions as a linear scaling force variability with respect to the mean force level (Jones et al., 2002).

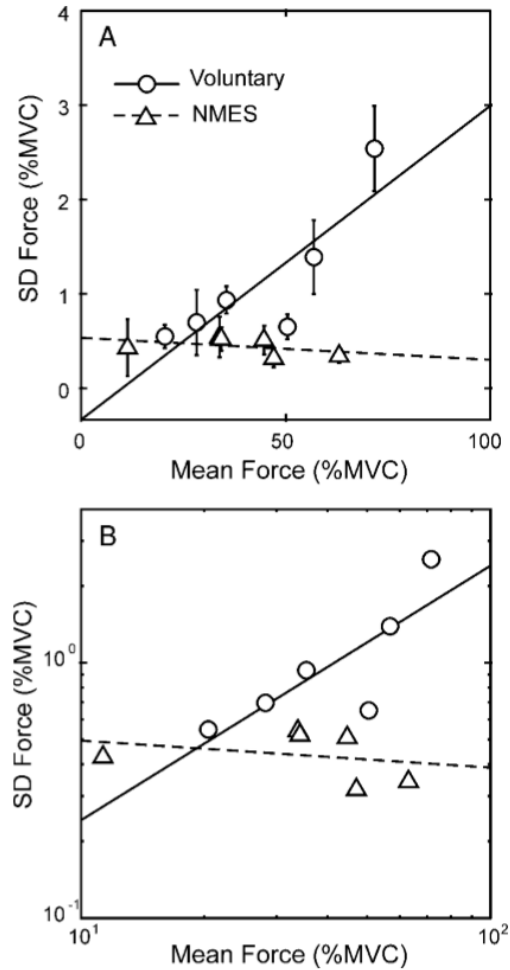


Figure 1: The scaling of force variability with respect to mean force output. A: data from 1 subject is shown. The SD of the force output is positively correlated to the mean force only in the voluntary condition. B: Same data as above, plotted on a log-log scale with regression lines to determine SDN exhibits linear scaling, i.e., slope = 1.0. Slope in the voluntary condition is 0.99 and in the NMES condition is -0.10, but the latter was not significant (Jones et al., 2002).

Multiplicative noise is particularly important in prosthesis control, as it is present in electromyographic (EMG) signals, which are used as the input to control myoelectric prostheses (Smith et al., 2016). EMG signals can be used to control a myoelectric

prosthesis, by rectifying and low-pass filtering the signal (Figure 2) (Clancy, Morin, & Merletti, 2002).

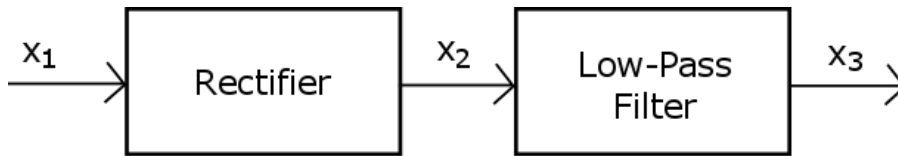


Figure 2: Processing of EMG signal

The raw EMG signal is represented by x_1 and contains some variance σ_1^2 . The output, x_3 , is the filtered signal. It is important to note that x_3 , which is used as the input to the myoelectric prosthesis, also has variance σ_3^2 . The variances of x_1 and x_3 are functions of the signal amplitude, so the multiplicative noise can be represented as a Gaussian distribution with mean zero and variance proportional to the squared control signal u ,

$$n \sim N(0, \sigma^2 u^2).$$

Our control amplitude is accordingly proportional to the variance of the myoelectric signal, which in turn is proportional to the effort (Parker et al., 1977; Shadmehr & Mussa-Ivaldi, 2012; Zecca et al., 2002). However, even after processing, the resulting signal itself contains multiplicative noise (Clancy et al., 2001; Hogan & Mann, 1980). The variance of a myoelectric signal, which is composed of a low-pass filter rectification of a signal with multiplicative noise, varies with amplitude.

This multiplicative noise is pervasive in biological systems. It influences human motor control and it must be accounted for in order to accurately describe many stereotypical human movements (Liu & Todorov, 2007). Some existing models have incorporated multiplicative noise into their dynamics, allowing them to explain phenomena such as asymmetric velocity profiles. However, they are unable to predict characteristics shown in more complex 2-DOF tasks, such as reaching to grasp a target, or operating 2 joints of a myoelectric prosthesis at the same time.

When humans make goal-directed arm movements, the neural control signals are corrupted by this multiplicative noise whose variance increases with the size of the control signal (Clamann, 1969; Matthews, 1996). Existing research supports that the underlying influence of trajectory planning is to minimize the variance of the position in the presence of biological noise (Harris & Wolpert, 1998). A mathematical simulation of a 1-DOF eye saccade by Shadmehr supports the minimum variance theory. As can be seen in Figure 3, the mathematical simulation aligns with real life data of an eye saccade. Asymmetric velocity profiles emerge in optimal control of a system that suffers from signal-dependent noise (also known as multiplicative noise) (Berniker & Kording, 2008; Shadmehr & Mussa-Ivaldi, 2012).

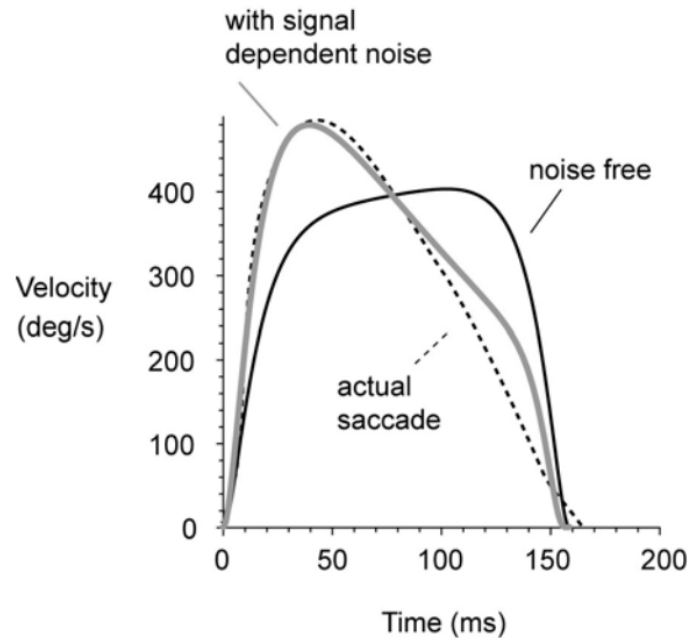


Figure 3: Velocity of Eye Saccade for a System with and without Noise (R Shadmehr & Mussa-Ivaldi, 2012)

2.2 SUBMOVEMENTS

A common stereotypical characteristic that exists in human movement is the presence of submovements. Movements are structured into phases composed of acceleration and deceleration, called submovements (Hofsten, 1991). Multiple submovements are observed mostly in infant reaching (Berthier, 1996), and in reaching movements by adults while completing difficult tasks, such as with a time constraint or an accuracy requirement (Kositsky & Barto, 2002). Reaching movements, composed of multiple submovements, are described as consisting of two phases (Smeets & Brenner, 1999). The first is the reaching phase and is the largest in terms of time and distance, consisting of 70-80% of the total movement time. The second phase is geared towards making finer adjustments, such

as endpoint accuracy (Hofsten, 1991). Mathematically, submovements can be described as a pair of zero crossings in the jerk profile (Fradet, Lee, & Dounskaia, 2009).

Kositsky and Barto illustrated how submovement sequences can emerge in a reinforcement learning system naturally, as an optimal control policy in response to feedback. Figure 4 displays the results of this research. The two phases of acceleration and deceleration, known as submovements, can be seen in Figure 4 (b).

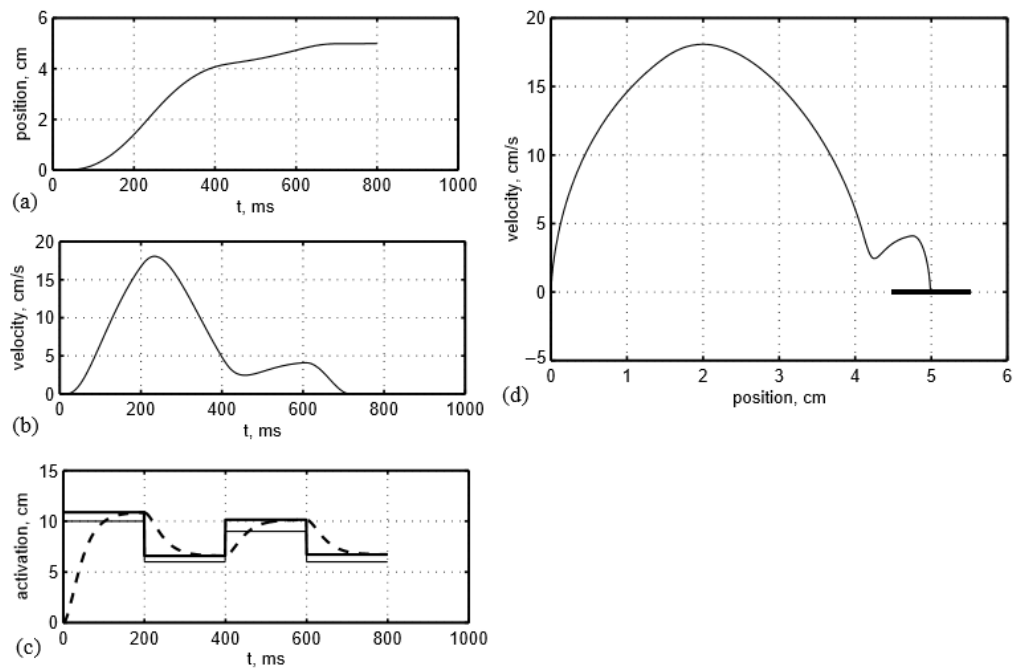


Figure 4: A Sample Movement from the Kositsky and Barto Simulation, Accomplished by the Controller after Learning (Kositsky & Barto, 2002).

The standard view of submovements is that they emerge due to the presence of feedback (Fishbach, 2007; Kositsky & Barto, 2002; Meyer, et al., 1988). Currently, existing models describe submovements emerging from the presence of feedback itself, and states that humans only produce corrective movements at the end of a movement as a response to a visual error that they are seeing (Elliott, Helsen, & Chua, 2001; Scheidt, 2005; Woodworth, 1899). Therefore, the optimal behavior in the presence of feedback is to produce submovements.

It is thought that visual feedback provides accuracy advantages, even for very rapid movements (Carlton, 1992; Keele, 1968). Keele and Posner concluded that the time required for the visual feedback loop to operate was somewhere between 190 and 260ms. It was also determined that occluding the vision of the hand and target approximately 290ms prior to the termination of the movement had little to no impact on performance (Schmidt, 1976; Keele, 1968). Once the execution of a submovement has begun, it continues unchanged by feedback until it is completed. Thus, it was suggested that visual information is most important prior to the initiation of any submovement (Meyer, Smith, Kornblum, Abrams, 1990).

Temporal constraints of a movement affect the opportunity for a second submovement. At movement times of approximately 450ms during a movement task, Posner and Keele observed that there was no difference between errors in feedback trials vs non-feedback trials, because the movement now only involved an initial impulse and no second submovement. Thus, the usefulness of the feedback depends on the temporal constraint of the trial(Keele, 1968).

Empirical evidence often displays two submovements, in which the first movement undershoots the target, and the second is a small corrective movement. It is more economical, in terms of both time and energy, to correct a movement that falls short of the target than to correct an overshoot (Carlton, 1992; Barrett, 1989). The initial ballistic movement is organized in a manner designed to minimize the temporal costs associated with error in the initial trajectory (Guiard, 1993). In most multi-DOF aiming tasks, target overshoots will be more time consuming than target undershoots. Overshooting requires a movement reversal which translates to an added temporal and energy cost.

However, there is a potential alternative explanation for the emergence of submovements that does not depend on the role of feedback. It is possible that for some tasks and cost-functions, producing submovements is actually the optimal behavior, even in the absence of feedback. Due to the dissipative, cumulative dynamics of the system, a higher control signal can be afforded earlier in the task, as the noise is dampened. This allows for a larger submovement at the beginning of the task, and then a smaller corrective one, even in the absence of feedback.

Human behavior in simultaneous control can be described by multiple submovements, which may result from noise in the control signal, paired with visual feedback (Kositsky & Barto, 2002; Saunders & Vijayakumar, 2011). Multiple submovements are present in rehabilitation tasks and myoelectric prosthesis control when the user attempts to control multiple degrees of freedom simultaneously (Smith et al., 2016).

2.3 CONTROL OF MULTI-DOF SYSTEMS

Smith et al. highlighted the importance of providing simultaneous control and the ability to isolate individual DOFs when desired while using a prosthesis (Smith et al., 2016). They found that subjects used more 1-DOF movements at the end of the trial, typically for fine corrections (Figure 5).

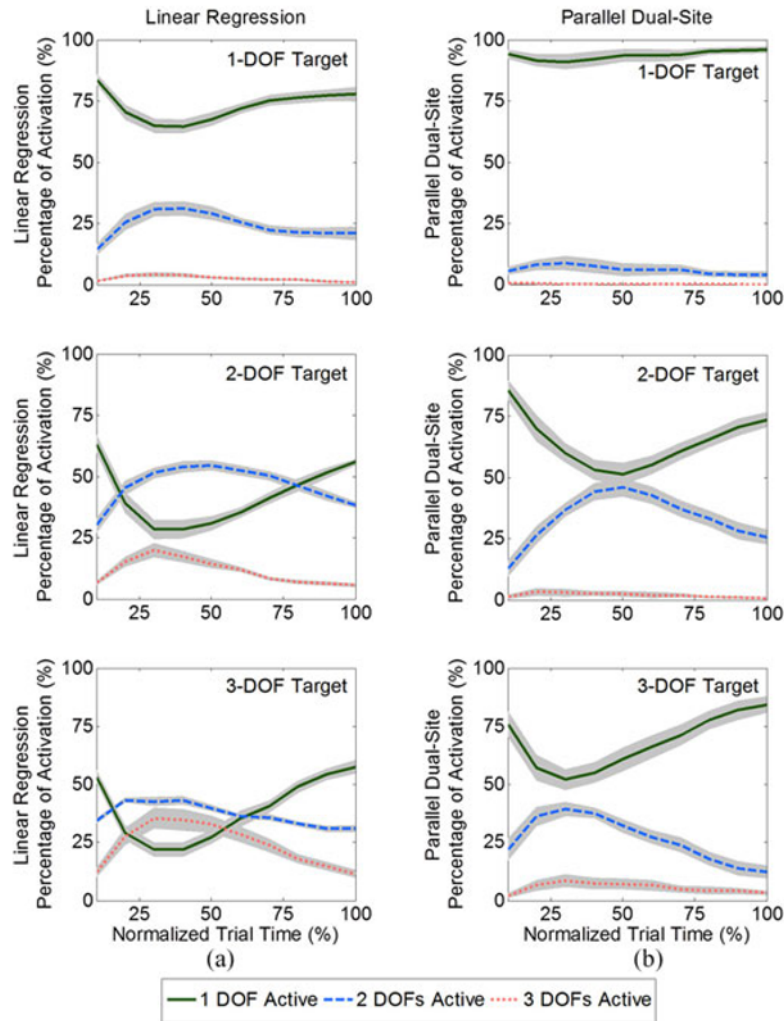


Figure 5: Distribution of DOF Allocation in Smith et al. Experiment (Smith et al., 2016)

Figure 5 depicts profiles of simultaneous control use, as a function of normalized trial time during myoelectric control of a virtual 3-DOF wrist/hand system (Smith et al., 2016).

For both the linear regression model and the parallel dual-site model, participants used more 1-DOF movements at the end of the trial for fine correction.

Modeling simultaneous multiplicative noise explains the phenomenon that we observe in human operating systems that have cross-talk between myoelectric sensors. Cross-talk refers to an unwanted transfer of signals between communication channels (Clancy, Bouchard, & Rancourt, 2001). When using electrodes to record EMG signals, the activity of the muscle over which the electrode is placed is recorded, as well other nearby muscles due to tissue volume conduction. Depending on the location and proximity of the electrodes, cross-talk is known to occur in surface EMG recordings (Kilner & Baker, 2002).

Shadmehr's 1-DOF model of human movement did not incorporate feedback, as the motor commands during an eye saccade do not have access to sensory feedback regarding the state of the eye. Typical saccades are too brief for visual feedback to influence the saccade trajectory, as the typical eye saccade ends after about 100ms, which is too short for the visual feedback loop to operate. Proprioceptive signals from the eyes do not play a significant role in controlling the trajectory of the eye (Shadmehr & Mussa-Ivaldi, 2012).

In this work, we extended existing 1-DOF models of a human performer which have previously incorporated multiplicative noise terms in order to explain asymmetric velocity profiles in 1-DOF movements (Shadmehr & Mussa-Ivaldi, 2012). We introduced new multiplicative simultaneous noise terms, κ_{Sx} and κ_{Sy} , that can account for the noise contributed by crosstalk, in order to better simulate the trajectories of realistic 2-DOF human movement. The dynamics of a human muscular system are cumulative (Shadmehr & Krakauer, 2008). The endpoint variance of a movement can be expressed as the

cumulative effect of the moment-by-moment dynamics and the size of the control signal, u . When this is represented mathematically, we observe that the effect of multiplicative noise early on in the control signal is substantially dampened out by the dissipative dynamics, and the noise later on in the movement is multiplied by the dynamics raised to a higher power (Hill, 1938).

3 MATHEMATICAL MODEL

Specific Aim 1: To evaluate whether or not simultaneous multiplicative noise influences the optimal control strategies of 2-DOF human movement. The working hypothesis is that the level of simultaneous multiplicative noise inherent in the control signal influences the degree of simultaneity, as well as the number of submovements that are made in the movement. To accomplish this aim, we developed a mathematical model that simulated a 2-degree-of-freedom reaching task.

Innovation. Much experimental and computational work has been directed toward developing theories that attempt to explain the behavior and regularity of our movements. Efforts in the field of motor control have focused on normative laws, or cost functions, that govern our behavior (Shadmehr & Mussa-Ivaldi, 2012). This work applies and expands these theories to create a model-based approach that aligns with the behavioral choices that humans consistently make during simultaneous control.

Significance. Reliable simultaneous control of multiple DOFs is not yet available for powered prostheses (Smith et al., 2016), which limits the performance of these devices compared with body-powered prostheses and able-bodied control. This model-based approach expands our knowledge of the strategies and regularity underlying human movement during simultaneous control. Eventually, this could have the potential to lead to improved control strategies that incorporate the role of feedback, control noise, and electrode placement.

3.1 METHODS

3.1.1 Extension of Mathematical Model

In order to observe the effects of adding new simultaneous noise terms to multi-DOF movement, we extended a 1-DOF mathematical model described by Shadmehr (Shadmehr & Mussa-Ivaldi, 2012). The existing model is a continuous representation of a linear system, and demonstrates that multiplicative noise is the cause of the asymmetry in 1-DOF velocity profiles (Jones et al., 2002). Our intent was to extend this model to 2-DOF, and incorporate new noise terms (κ_{sx} and κ_{sy}) proportional to the degree of simultaneity of the movement in order to explain inherent characteristics in the velocity profiles. The 2-DOF model consisted of two independent joints, which are coupled by simultaneous noise. The dynamics of our system are represented by

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{bu}, \quad (1)$$

where \mathbf{x} is the vector of state variables, $\mathbf{x} = [x \ \dot{x}]^T$, A is the dynamical matrix, b is the control matrix, and \mathbf{u} is the control input vector. The cost function for the task was composed of three terms: the endpoint accuracy, the effort exerted, and the time p that it took to complete the task. The cost function of time is represented as

$$J_t = \alpha \left(1 - \frac{1}{1 + \beta p} \right), \quad (2)$$

where α is the arbitrary value that we assigned to completing the task, and β is the rate at which we temporally discounted this value. The cost of the effort exerted during the task was equal to the integral of the muscle activation u squared (the energy).

$$J_e = \lambda \int_0^p u^2(t) dt, \quad (3)$$

where λ is the relative cost that is incurred for the motor commands. A cost for endpoint accuracy is defined based on the learners' distance from the target at the end of the trial.

$$J_a = \tau(x(p) - g)^2, \quad (4)$$

where τ is the relative cost incurred for being inaccurate, and g is the desired final position of the target. The cost function for the task is a summation of (2) - (4),

$$J = J_t + J_e + J_a, \quad (5)$$

Optimizing for this cost function leads to the following optimal control law,

$$\mathbf{u}(p) = (L + \Gamma^T F^T C^T T C F \Gamma + \kappa^2 S)^{-1} \Gamma^T F^T C^T T (\mathbf{r} - C A^p \mathbf{x}^{(0)}) \quad (6)$$

The goal of the learner model was to perform the optimal motor command u for a given movement, to minimize the cost function (5). Our work expanded on an existing mathematical model which already contains a multiplicative noise term for the movement [Appendix A]. We added new simultaneous multiplicative noise terms κ_{Sx} and κ_{Sy} to the existing model to observe its effects for a 2-DOF reaching movement. When we took the expected value of the variance in the state squared, it added an offset to the optimal control law. The optimal control input for the X-DOF and Y-DOF then became

$$\mathbf{u}_x = \frac{\Gamma^T F^T C^T \mathbf{r} [\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L - \kappa_{Sy} S]}{(\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L)(\Gamma^T F^T C^T T C F \Gamma + \kappa_y^2 S + L) - S^2 \kappa_{Sx} \kappa_{Sy}} \quad (7)$$

and

$$\mathbf{u}_y = \frac{\Gamma^T F^T C^T \mathbf{r} [\kappa_{Sx} S - \Gamma^T F^T C^T T C F \Gamma - \kappa_y^2 S - L]}{S^2 \kappa_{Sx} \kappa_{Sy} - (\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L)(\Gamma^T F^T C^T T C F \Gamma + \kappa_y^2 S + L)} \quad (8)$$

where

$$F = [A^{p-1} \ A^{p-2} \ A^{p-3} \ \dots \ I],$$

$$\mathbf{r} = \begin{bmatrix} g \\ 0 \\ 0 \end{bmatrix},$$

$$\Gamma \equiv \begin{bmatrix} \mathbf{b} & 0 & \dots & 0 \\ 0 & \mathbf{b} & 0 & 0 \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{b} \end{bmatrix},$$

$$T \equiv \begin{pmatrix} v_1 & 0 & 0 \\ 0 & v_2 & 0 \\ 0 & 0 & v_3 \end{pmatrix},$$

$$S = \text{diag}[\Gamma^T F^T C^T T C F \Gamma],$$

and v is composed of three tracking cost parameters, $v = [5 \times 10^9, 5 \times 10^{-11}, 80]$ (Shadmehr & Mussa-Ivaldi, 2012). The observability matrix is represented as C , and L is a matrix that represents the relative cost λ at each time point. Both C and L are set to the identity matrix for our simulations ($\lambda = 1$).

The terms in our control signals, which contain κ_{Sx} and κ_{Sy} , did not exist in the previous mathematical model. Due to the nature of S , the noise terms promoted movement at the

beginning of the task rather than the end, as a higher cost is incurred at the end of the movement.

The goal of the simulation was to produce control signals that minimize a cost function in a 2-DOF task, so that these control signals could be used to observe movement characteristics such as velocity profiles and degree of simultaneity.

3.1.1 Analysis

3.1.1.1 Submovement Analysis

Models that implicitly generate submovements capture an important element of human motor control. Researchers have argued that submovements represent the least divisible unit of a motor action (Dipietro et al., 2009). Submovements are defined by phases composed of acceleration and deceleration in the velocity profile of the control task (Hofsten, 1991). Here we identify submovements as each pair of jerk zero-crossings in the acceleration profile of the movement, an example of which can be found in the analysis of our model (Fishbach et al., 2007). By understanding how to model submovements, we move towards understanding how these movements break down in disordered human behavior.

3.1.1.2 Simultaneity Analysis

A measure of simultaneity enables us to address how control is allocated across 2-degrees-of-freedom (Masliah, 2001). The simultaneity of the movement is described by the degree in which the two DOFs were operating at the same time, and is represented in our mathematical simulation by:

$$Simultaneity[n] = \frac{\min(u_x[n], u_y[n])}{\max(u_x[n], u_y[n])}, \quad (9)$$

where $n \in [1, p]$.

If both control signals are the same value, the simultaneity is 1. If one control input is on while the other is off, or both are off, the simultaneity metric value is zero.

3.2 SIMULATION RESULTS

The results of the simulated model were analyzed using the velocity profile of the movement to observe the submovements, and the degree of simultaneity of the two degrees-of-freedom. The spatial trajectory of the movement in the x-axis displays the path as the target is reached (Figure 6). In the case with only multiplicative noise, the velocity profile is asymmetrical with no submovements present (Figure 7). The asymmetric velocity profile is present because it minimizes the variance of the movement (Harris & Wolpert, 1998). Errors at the beginning of the task costs less than errors towards the end, as the dynamics of the system are dissipative. The spring-stiffness term, k , is also required to create the asymmetric velocity profiles and the emergence of submovements [Appendix A].

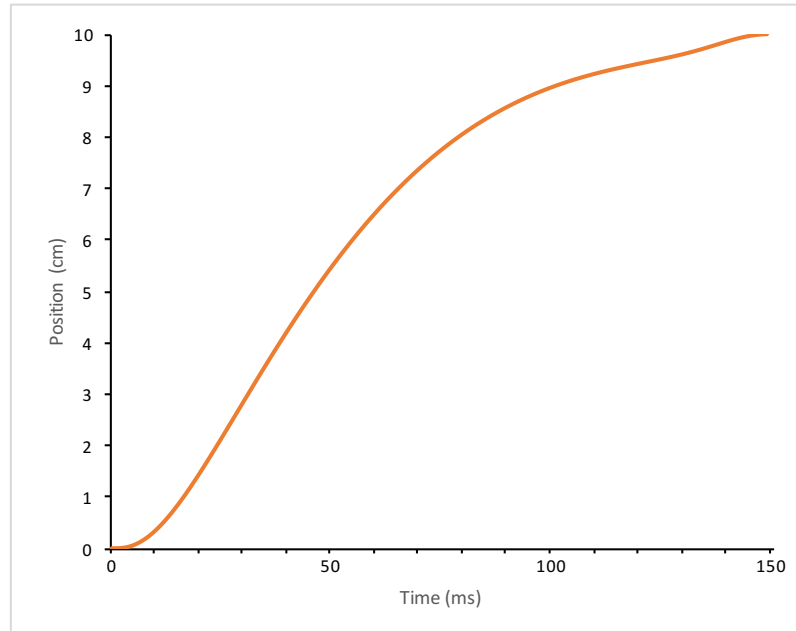


Figure 6: Spatial Trajectory of 2-DOF Movement, Position in X Direction (cm)

3.2.1 Submovements

The velocity profiles in both the X-DOF and Y-DOF were asymmetric in the case of a system with simultaneous and multiplicative noise (Figure 7). They both display a high initial velocity for the first submovement, and a second smaller submovement, with a peak velocity of approximately 20% of the first submovement. The peak of the first submovement in the X-DOF is larger than that of the Y-DOF, and the peak of the second submovement is smaller. This difference is due to the noise parameters being set slightly differently for each DOF in order to avoid a singularity.

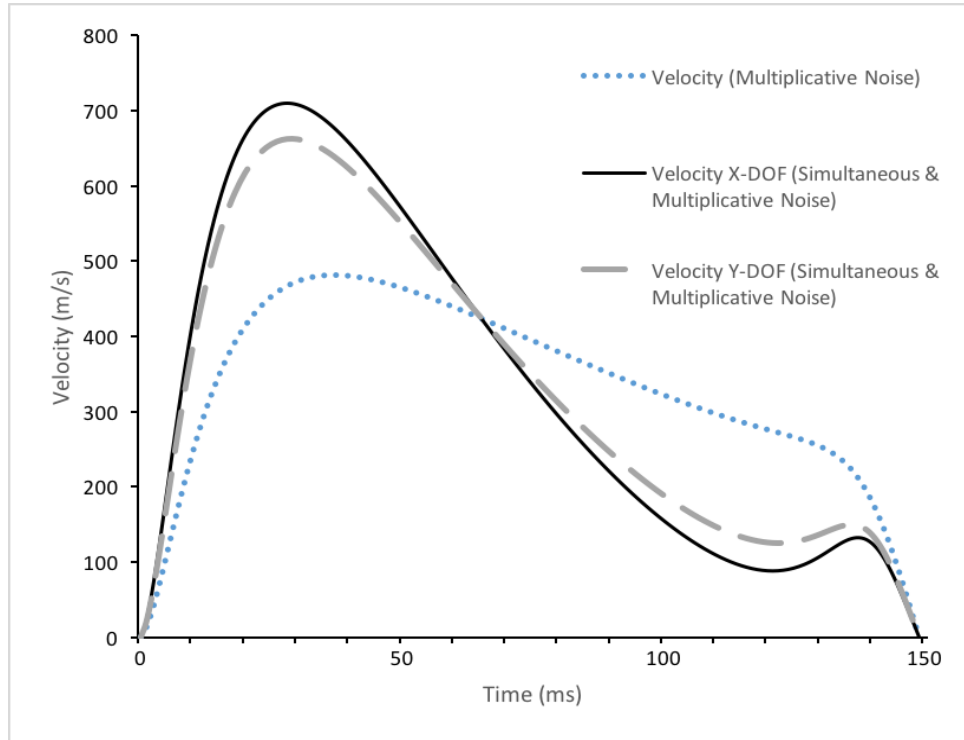


Figure 7: Velocity Profiles of a 2-DOF Movement, with and without Multiplicative Simultaneous Noise. ($\kappa_{Sx} = 8 \times 10^{-11}$, $\kappa_{Sy} = 10 \times 10^{-11}$).

When the X-DOF and Y-DOF are not coupled by simultaneous noise, each DOF behaves as a 1-DOF movement, producing only one submovement (see dotted blue line in Figure 7). In contrast, when simultaneous multiplicative noise was injected into the system, four zero crossings emerged in the jerk profile of our simulation, which illustrates two submovements (Figure 8).

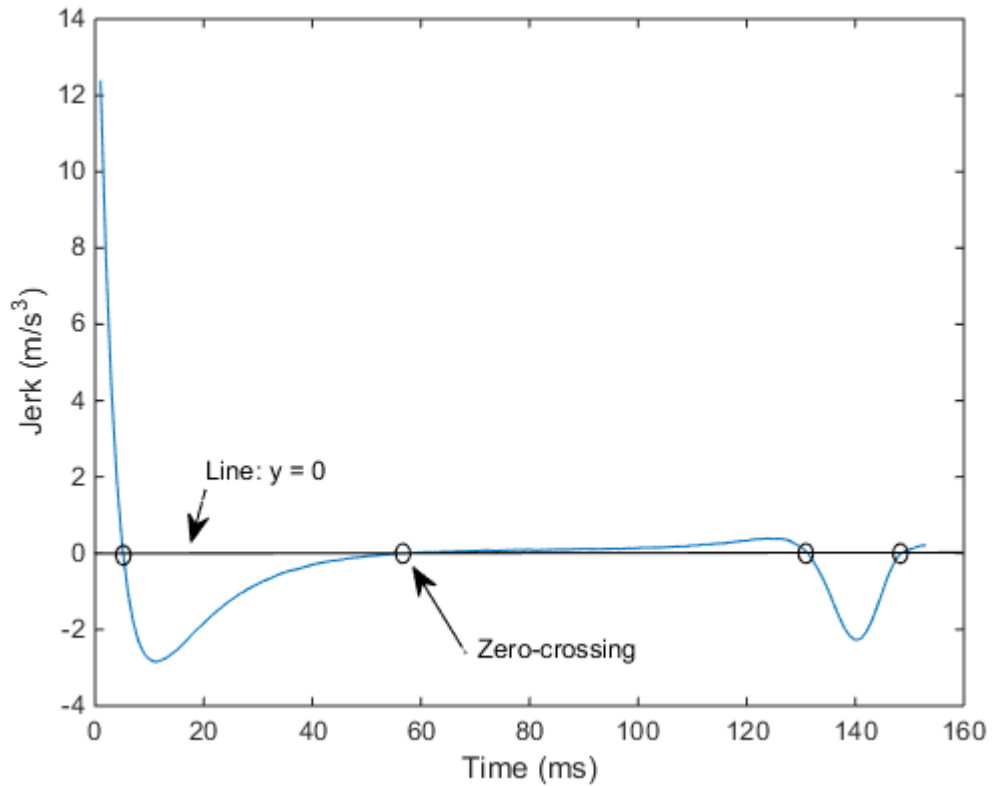


Figure 8: Jerk Profile of a 2-DOF Movement, with Multiplicative Simultaneous Noise

Due to the dissipative nature of the dynamics of the system, movements at the beginning of the task incur less cost than near the end. The simultaneity of the movement is 100% at 57ms and 131ms which corresponds to the crossover in the control signals u_x and u_y (Figure 9). The simultaneity of the movement was higher at the beginning of the movement and decreased near the end.

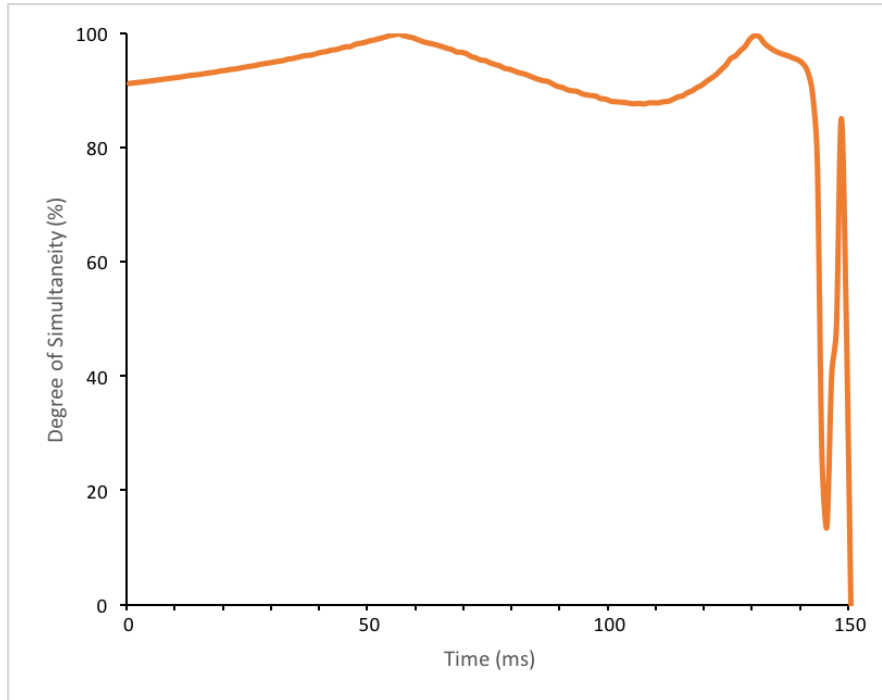


Figure 9: Degree of Simultaneity between the X-DOF and Y-DOF of a 2-DOF Task with Simultaneous Noise

3.3 MATHEMATICAL SIMULATION SUMMARY

The goal of our mathematical model was to evaluate whether or not the simultaneous multiplicative noise influences the degree of simultaneity of the control. Our hypothesis was that the level of simultaneous multiplicative noise inherent in the control signal influences the degree of simultaneity. By extending an existing mathematical model to 2-DOF, and adding a simultaneous noise term, we were able to mathematically simulate a 2-DOF movement (Shadmehr & Mussa-Ivaldi, 2012). We found that in the presence of a simultaneous noise term, submovements emerged, even in the absence of visual feedback. The simultaneity of the movement decreased for a brief period at the very end of the task. This decrease in simultaneity is the optimal strategy due to the cumulative dynamics of the system. It is optimal to operate in 1-DOF at the end of the movement, moving sequentially.

4 EXPERIMENTAL VALIDATION

Specific Aim 2: To test the findings of Aim 1 on humans to assess whether the simultaneous multiplicative noise in the control signal affects the optimal control strategies in a 2-DOF task. The working hypothesis is that by adding simultaneous noise, submovements will emerge in the velocity profile of the movement, and the degree of simultaneity will increase. To accomplish this aim, we tested 28 able-bodied subjects in a discrete psychophysics experiment, and analyzed the results.

Innovation. The experimental research in the field of motor control has observed the emergence of submovements in the presence of visual feedback (Smith et al., 2016). This work expands existing research and tests for the emergence of submovements, even in the absence of visual feedback, which has not been predicted previously.

Significance. Reliable simultaneous control of multiple DOFs is not yet available for powered prostheses (Smith et al., 2016), which limits the performance of myoelectric prostheses compared with body-powered prostheses and able-bodied control. Experimental validation of our mathematical model expands our knowledge behind a potential reasoning for the stereotypical characteristics of human movement during simultaneous control. Validating the theoretical model empirically supports our models predictions by providing actual human data.

4.1 METHODS

4.1.1 Experimental Protocol

To explore whether the predictions of the mathematical simulation matched actual human movements, a 2-DOF discrete task incorporated into a video game was designed.

A human participant was asked to control a rocket on a screen using the up and right arrow keys to reach a target. To ensure that the dynamics of the system were constant, the refresh rate of the image was coded in absolute time to be 0.03s (33Hz). The velocity of the rocket was proportional to the control input for each DOF separately based on whether the key was on/off. Each trial had two stop criteria – a cut-off time of 5 seconds or a dwell time of 0.5 seconds. If the participant exceeded 5s to complete the trial, the trial ended automatically. If the participant was not pressing a key for 0.5s, the trial would also end. MATLAB 2014A was used with the Psychtoolbox3 in Windows 10 (Brainard, 1997). The full MATLAB experimental code can be found in Appendix B.

Data were collected from 28 subjects, 14 in the control group (multiplicative noise only) and 14 in the experimental group (multiplicative and simultaneous noise). There were 3 phases to the experiment: exploration, training and testing. The details of the set-up for each phase can be found in Table 1.

Table 1. Details of Experimental Phases

Phase	Clock Present?	Score bar Present?	Visual Feedback?			# of Trials	Length of Time
			Block 1	Block 2	Block 3		
Exploration	Yes	No	N/A	N/A	N/A	N/A	12 min
Training	Yes	Yes	Yes	Every 4th trial	Every 4th trial	45	N/A
Testing	Yes	Yes	Yes	Every 4th trial	Every 4th trial	150	N/A

During the training and testing phases of the experiment, subjects were able to see their score after every trial via a score bar on the right side of the screen (Figure 10).

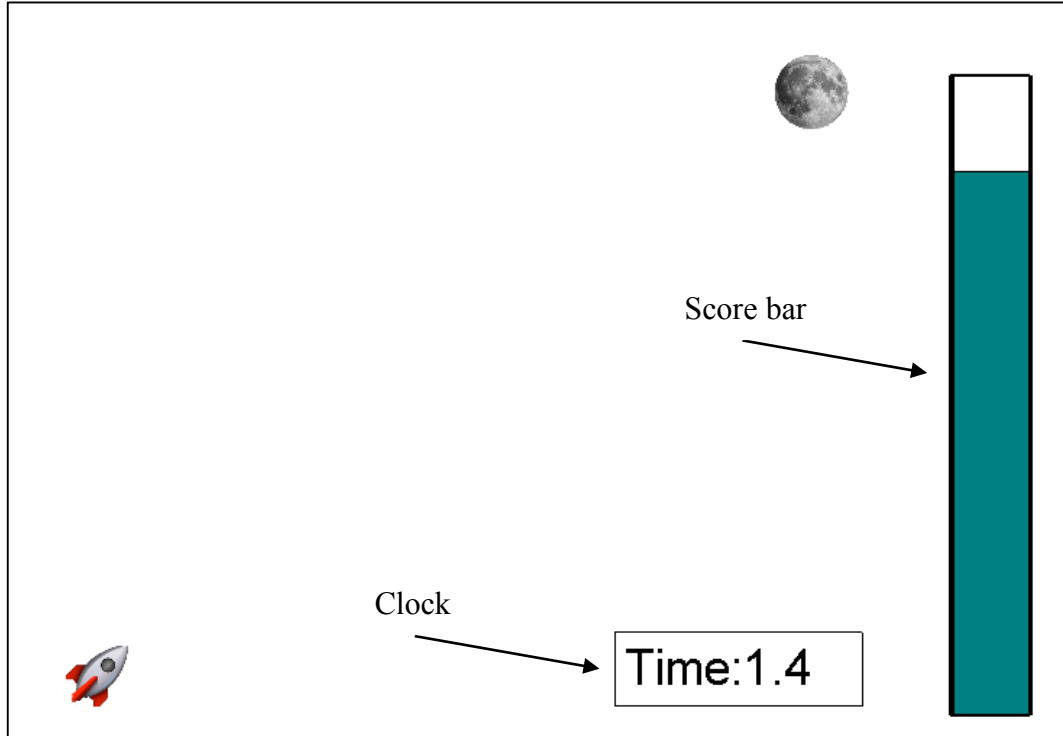


Figure 10: Experiment Testing and Training Screen

Group 1 experienced a multiplicative noise term of 0.006. In both the x and y-axis, a normally distributed random number between -1 and 1 was multiplied by 0.006 and added to the position of the rocket. The simultaneous noise term was zero for this group. The noise was incorporated into the each separate DOF of the system as follows:

$$noise = 0.006 * rand$$

$$n = n + 1, \text{ if button is being pressed}$$

$$n = n - 1, \text{ if button is not being pressed}$$

$$x = x + 0.00035 + 0.035n + noise$$

Where x is the position of the rocket, n is a counter, and $rand$ is a random number between -1 and 1.

Group 2 experienced a multiplicative noise term, $\kappa = 0.006$ as well as a simultaneous noise term of $\kappa_{sx} = \kappa_{sy} = 0.01$, which was introduced to the movement in the same approach as the multiplicative noise. The simultaneous noise term was only present when both the up and right arrow keys were active at the same time. This weighting was selected from the pilot study, in which the noise parameters were tweaked in order to hone in on the ideal noise level that would promote both simultaneous movement and discrete movement. Informal user feedback was used to achieve the goal of tuning the simultaneous noise to be high enough for there to be a higher accuracy when operating discretely, but low enough for there to be incentive to operate simultaneously to save on time.

4.1.1.1 Exploration phase

During the exploration phase, the subjects were shown four control strategies, as illustrated in Figure 11, where the red star is the initial position and the black star is the target position. Subjects were given three minutes to explore each control strategy, and the strategies were randomized for each participant. The subjects had continuous visual feedback of their trajectory during this phase as well as a clock that displayed the length of time it took them to complete the trial. During this phase, subjects did not have access to their total score. When running the experiment with simulated control signals, all four control signal options resulted in approximately the same score. Therefore, it is possible that the subjects did not rely on the score bar, and simply used the clock and the endpoint accuracy as feedback for their success of the trial. The goal of the exploration phase was to acclimate the subjects to all control strategies before data collection began.

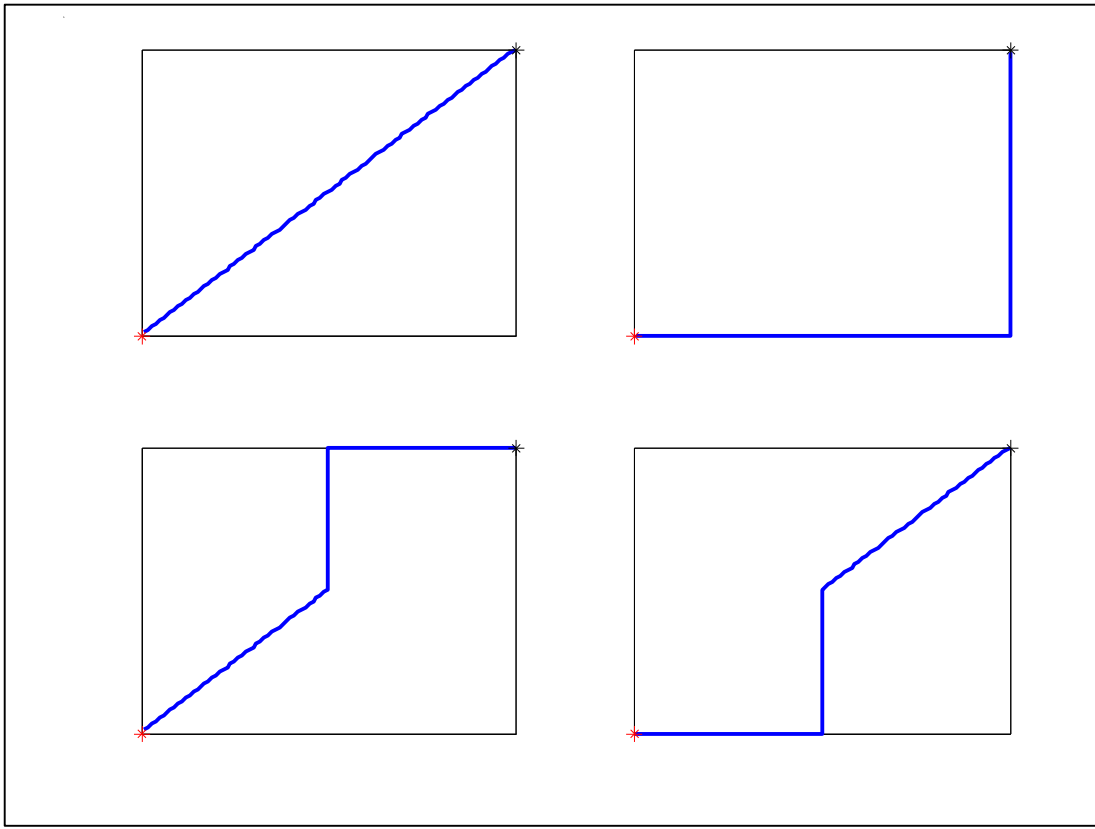


Figure 11: Control Strategies for the Exploration Phase. A red star is the initial position and the black star is the target position.

4.1.1.2 Training Phase

A score was computed as a weighting between movement duration and endpoint error in order to create a time-accuracy tradeoff. The length of time that the subject took to complete the trial was weighted at 20% of the score, and endpoint error (L1-norm) was weighted at 80% (40% in each DOF). This weighting was selected from a pilot study that was conducted on 6 subjects, which focused on choosing a score weighting that would promote both accuracy and fast trial time. The following equations were implemented to calculate the total score.

$$Time\ Score = \left| \frac{(Cutoff\ time - Dwell\ time) - (End\ time - Dwell\ time)}{(Cutoff\ time - Dwell\ time)} \right| * 20, \quad (10)$$

where

$$Cutoff\ time = 5s,$$

$$Dwell\ time = 0.5s,$$

$$End\ time = Time\ subject\ took\ to\ complete\ trial,$$

$$Accuracy\ X = 40 - \left| \frac{Target\ endpoint\ x - Trial\ endpoint\ x}{Target\ endpoint\ x} \right| * 40, \quad (11)$$

$$Accuracy\ Y = 40 - \left| \frac{Target\ endpoint\ x - Trial\ endpoint\ x}{Target\ endpoint\ x} \right| * 40, \quad (12)$$

where

$$Target\ endpoint\ x = 0.4, \text{ and}$$

$$Target\ endpoint\ y = 0.65.$$

The total score was calculated as

$$Total\ Score = Time\ Score + Accuracy\ X + Accuracy\ Y. \quad (13)$$

During this phase, participants completed 15 trials with visual feedback, and then 30 trials in which the visual feedback was turned off for 4 out of every 5 trials, for a total of 45 trials.

4.1.1.3 Testing phase

The testing phase was divided into 3 blocks of 50 trials, for a total of 150 trials. During the first block, continuous visual feedback was provided for every trial. In order to test whether multiple submovements were an optimal feedforward strategy (the ideal strategy in the absence of feedback), we removed the visual feedback during some portions of the following blocks. For blocks 2 and 3, visual feedback was only provided once every 4 trials. This frequency was selected as we wanted participants to receive feedback about their path, but not frequent enough to rely on it. Subjects were given a two-minute rest between each block. The experimental testing screen for this phase was the same as that of the training phase. Data analyzed came from this phase.

4.1.1.4 Subjects

Participants of this study were recruited to complete a computer task, using the up and right arrow keys on a standard keyboard. Subjects were recruited by oral communication and via e-mail and an online bulletin board within the University of New Brunswick and the local community. Data collection took place at the Institute of Biomedical Engineering at the University of New Brunswick. Participants were all above the age of 12, and participants under the age of 19 were required to obtain consent from a legal guardian prior to data collection. All participants played video games at least once a week, for a minimum of 4 hrs/week. This ensured that they were able to learn the control strategies in the time allotted. Participant numbers and demographics are outlined in Table 2.

Table 2. Participant Demographics

			AVG	SD
Gender	Female	n = 1		
	Male	n = 27		
Age Range (yrs)		15 - 31	22	4.3
Hrs Gaming/Week		4 - 40	13	7.5

Research ethics approval was granted by the University of New Brunswick under file number REB 2014-019. All parties provided consent by signing the consent form [Appendix C] and were fully informed that the participant would be exposed to minimal risk and that the participant’s welfare would be protected throughout the duration of the experiment.

4.1.2 Analysis

4.1.2.1 Submovement Analysis

For the experiment, as our control signal was either 0 or 1, we classified a submovement as a pair of changes from 0 to 1 and 1 to 0 in the control signal. When a key was “on” (pressed), it was represented as a 1 for that specific instance in time, and 0 if it was “off” (not pressed).

4.1.2.2 Simultaneity Analysis

For the analysis of the experimental data, the simultaneity of the movement was calculated as a percentage by summing the x and y control signals. Since the control signal was either 0 or 1, three states were possible as an outcome when summing the signals:

0 – Neither key was being pressed

1 – Either the up or the over arrow key was being pressed

2 – Both up and over arrow keys were being pressed

For the movement to be considered simultaneous, both keys were required to be pressed for at least 90% of the trial. For the trials that were not 90% simultaneous, we divided the trial in half and classified each half as either discrete or simultaneous by calculating the simultaneity of each half. It was found that this step was unnecessary, as subjects were either fully discrete or fully simultaneous. The participants were either always operating both keys, regardless of how many submovements they made (simultaneous), or they were only operating one key at any instance in time (discrete).

4.2 EXPERIMENTAL RESULTS

4.2.1 Statistical Analysis

A Shapiro-Wilk test was conducted to test for the normality of the data. As none of the parameters followed a normal distribution, a Mann-Whitney-Wilcoxon test was selected to test the significance of the data. The mean, median, 25% and 75% quartiles, and standard deviation (SD) were calculated for the trial time and endpoint error for all trials (visual and non-visual) and were reported in Table 3.

Table 3. Trial Time and Endpoint Error Summary

	Trial Time (s)		Endpoint Error X (%)		Endpoint Error Y (%)	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
Mean	1.76	1.94	15.09	16.03	16.09	17.11
Median	1.49	1.53	14.69	16.39	15.19	16.20
[25th-75th]	[1.46 – 1.97]	[1.46 – 2.44]	[11.29 - 17.2]	[14.53 –18.31]	[12.78–19.37]	[13.41 – 19.58]
SD	0.47	0.62	5.16	3.90	5.97	4.98

We found that subjects never maxed out the 5-second timer, with an average of 1.49s per trial for Group 1 and an average of 1.53s per trial for Group 2.

As the two data samples came from distinct populations, were independent, and did not follow a normal distribution, the Mann-Whitney-Wilcoxon test was used to assess the null hypothesis that the two population distributions had the same median.

The null hypotheses for Trial Time ($p = 0.259$), Endpoint Error X ($p = 0.159$) and Endpoint Error Y ($p = 0.248$) failed to be rejected as all p-values were greater than the 0.05 significance level. We were unable to conclude that that the trial times and endpoint errors for Group 1 (multiplicative noise only) and Group 2 (multiplicative and simultaneous noise) were different.

The number of submovements and percent simultaneity were calculated and reported in Table 4.

Table 4. Submovement and Percent Simultaneity Summary

	Submovements		Percent Simultaneity (%)	
	Group 1	Group 2	Group 1	Group 2
Mean	1.63	2.02	85.04	68.17
Median	1	1	98.70	95.57
[25th – 75th]	[1-1]	[1-2.78]	[92.79 -99.44]	[31.63-99.12]
SD	1.33	1.57	28.01	41.14

The Mann-Whitney-Wilcoxon test was conducted again to compare the percent simultaneity of the control strategies as well as the number of submovements in group 1 and group 2. We rejected the null hypothesis for the mean percent simultaneity of the movement, but failed to reject the null hypothesis for the mean number of submovements ($p = 0.142$). We found that at the 0.05 significance level, there was evidence that there was a difference in the percent simultaneity of Group 1 and 2 (Figure 12), but not in the number of submovements (Figure 13).

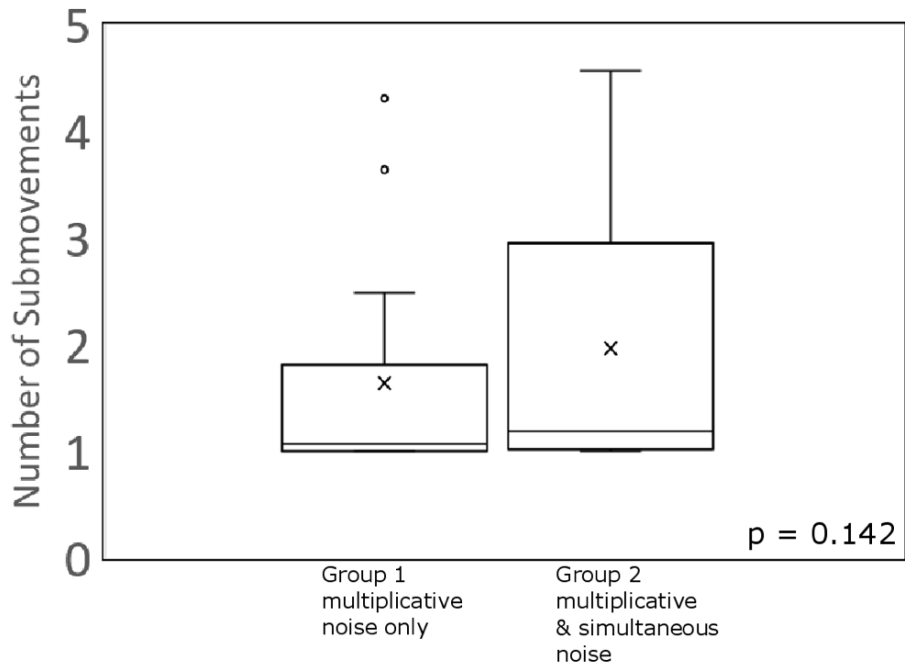


Figure 12: Box-plot of the Average Number of Submovements in Group 1 and Group 2

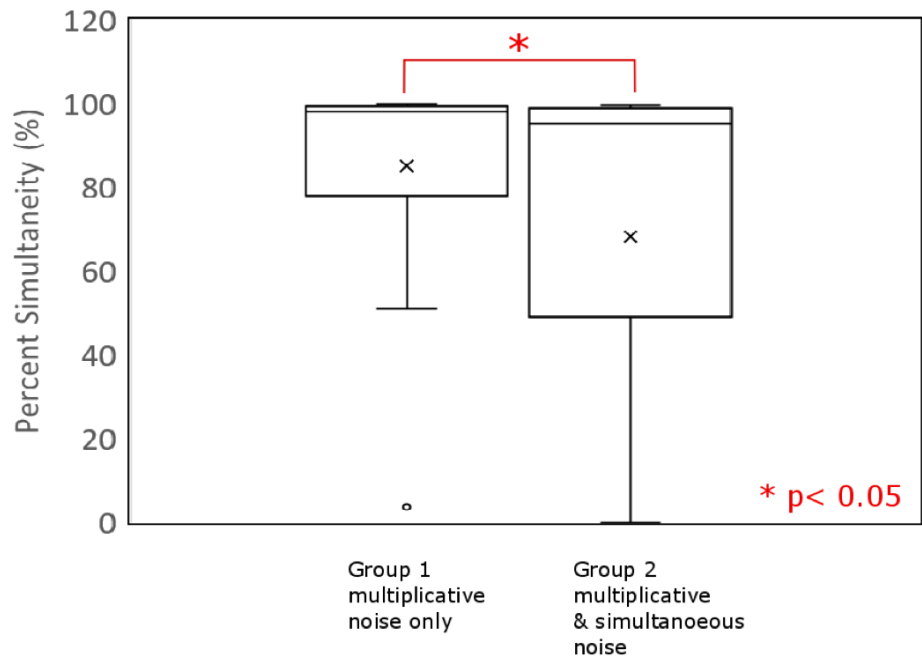


Figure 13: Box-plot of the Average Percent Simultaneity in Group 1 and Group 2

Group 2, which had simultaneous noise, used a less simultaneous control input when compared to Group 1, but there was no evidence found for a difference in submovements. We expected that the level of simultaneous noise would increase the number of submovements and decrease the percent simultaneity of the movements. However, the data only showed evidence to confirm our hypothesis that the number of submovements would increase with the increase of simultaneous noise.

4.2.2 Control Strategies

19% of subjects in Group 1 chose a discrete control strategy (only operating one key at a time), an example of which can be seen in Figure 12. 81% of Group 1 chose a simultaneous control strategy (always operating both keys at the same time), as seen in Figure 13. In Group 2, 37% of participants chose discrete control strategies while 63% of participants chose a simultaneous control strategy.

The results are as expected, due to the presence of the simultaneous noise term in Group 2, which adds more noise when operating both keys at the same time. As the dynamics are cumulative and dissipative, the optimal solution in the presence of simultaneous noise is to be less simultaneous in order to decrease the cost, especially at the end of the movement. As Group 1 did not experience the simultaneous noise term during the experiment, we expected this group to be more inclined to use the simultaneous control strategy as the data showed.

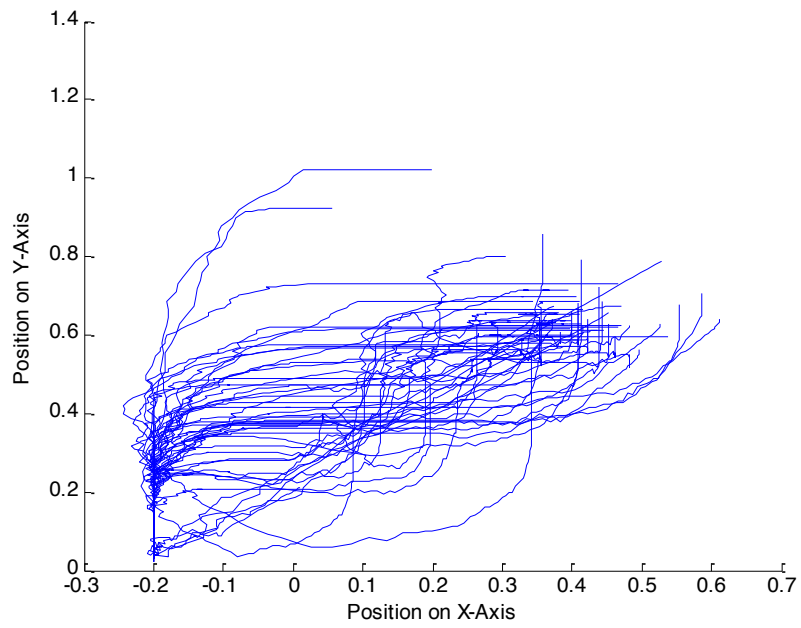


Figure 14: Discrete Control Strategy Sample, 50 Trials (No Visual Feedback)

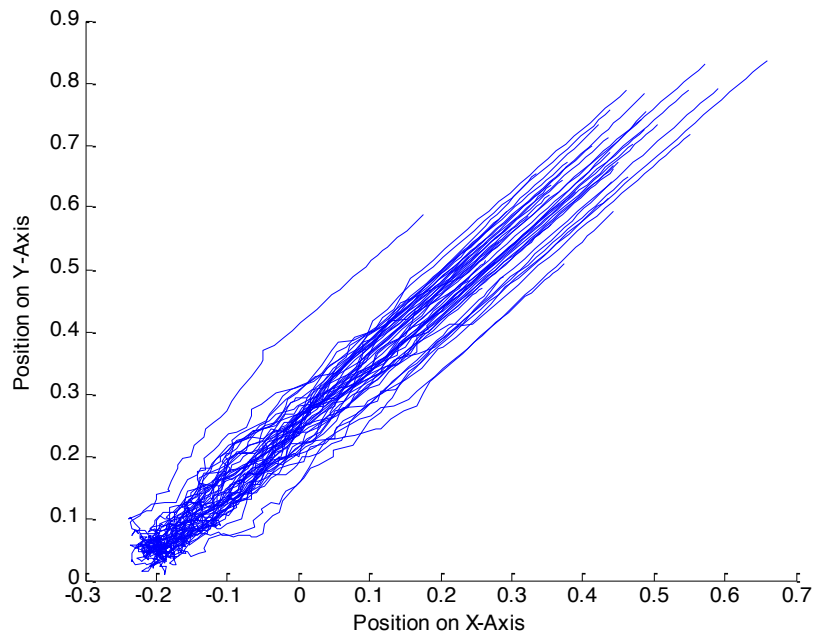


Figure 15: Simultaneous Control Strategy Sample, 50 trials (No Visual Feedback)

A depiction of the number of submovements of Group 1 and 2 are displayed for all trials (Figure 14 & 15). We found that in the presence of simultaneous noise, subjects did not produce a different amount of submovements than those who were not subjected to simultaneous noise.

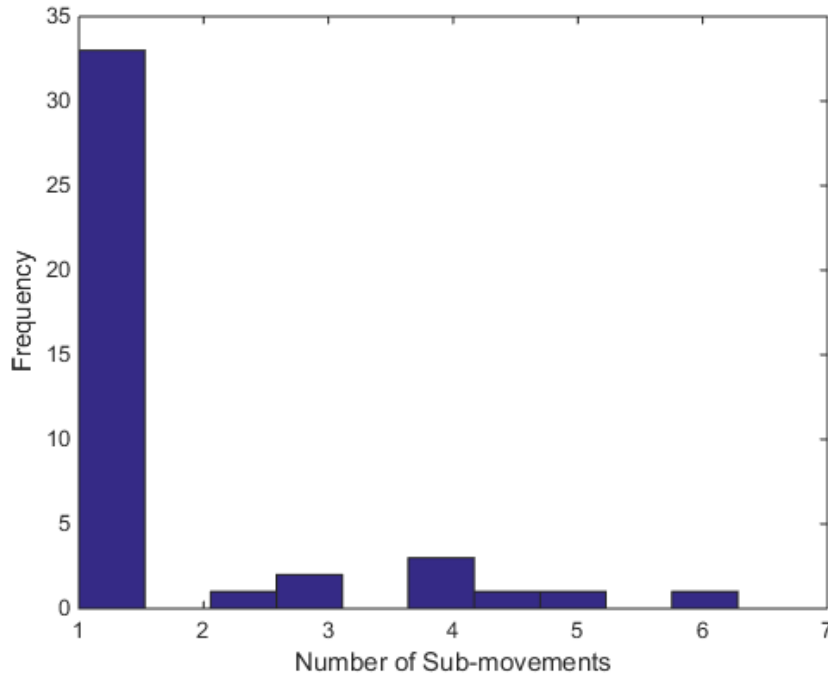


Figure 16: Histogram of Number of Submovements for Group 1

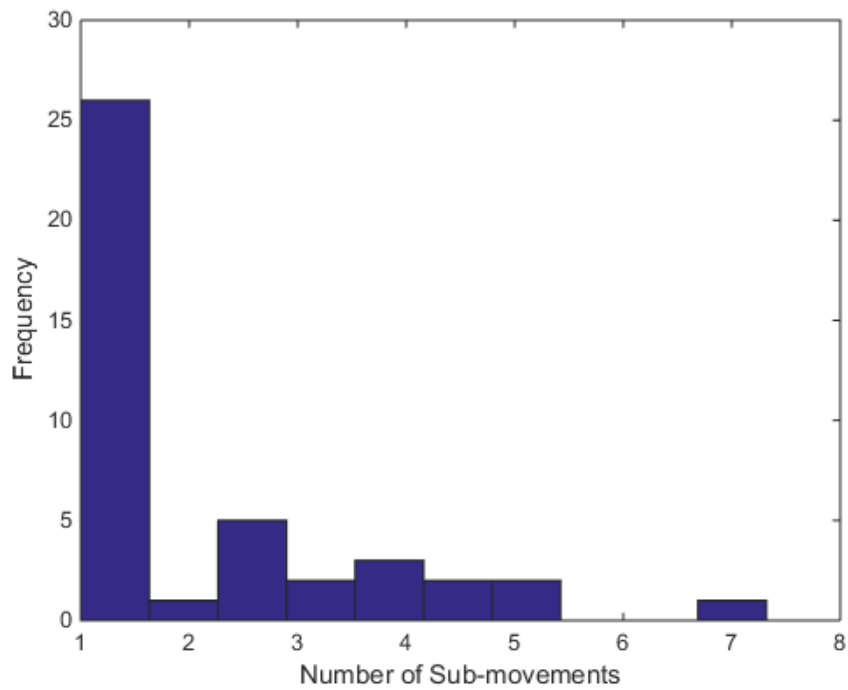


Figure 17: Histogram of Number of Submovements for Group 2

4.2.3 Percent Simultaneity

The percent simultaneity of the movement for each trial can be seen in Figure 16 and 17 for Group 1 and 2 respectively. Fewer trials were completed using discrete control strategies in Group 1 (0% simultaneity equates to 100% discrete movement) than Group 2.

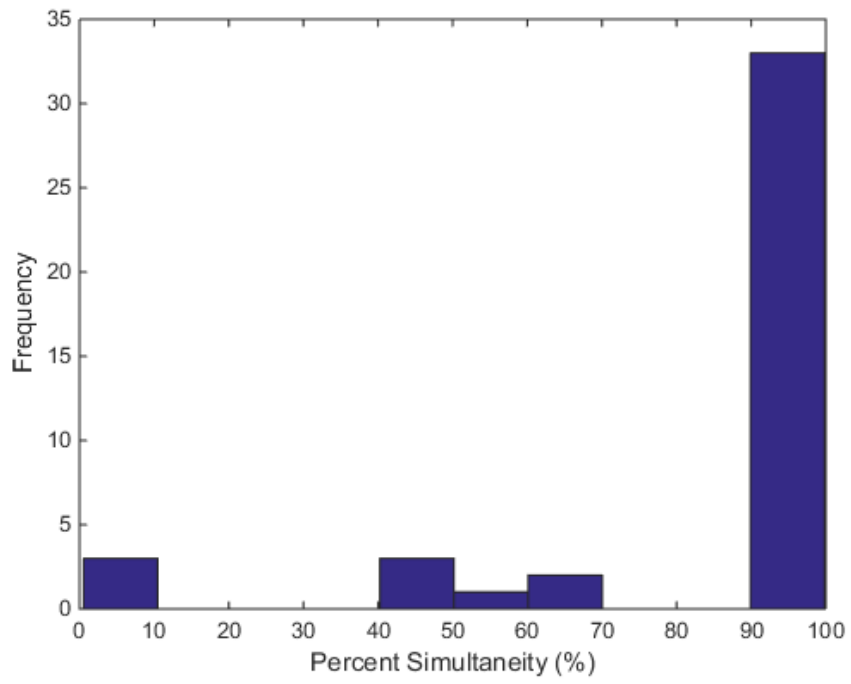


Figure 18: Histogram of Percent Simultaneity for Group 1

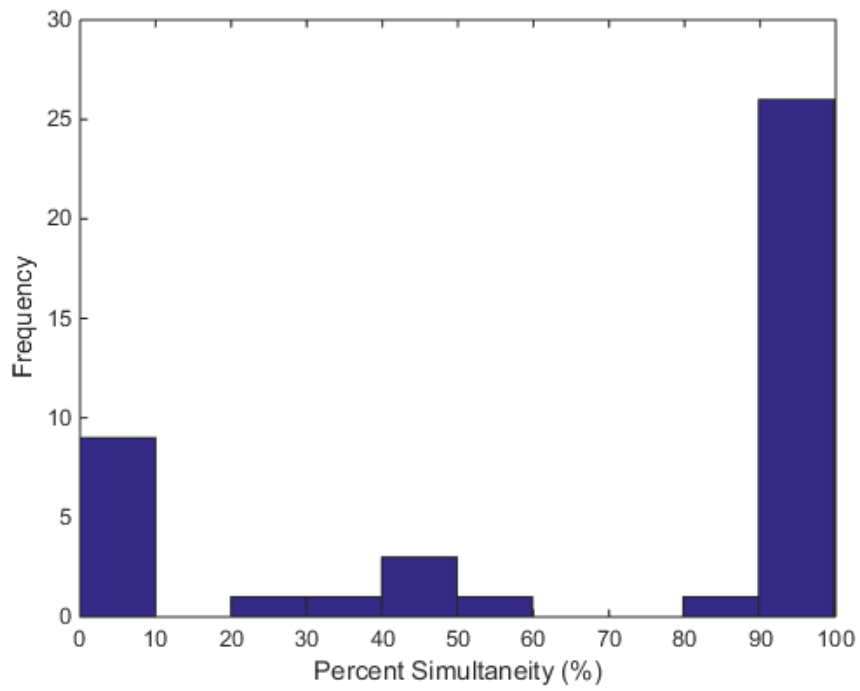


Figure 19: Histogram of Percent Simultaneity for Group 2

2.2.4 Visual Trials vs. Non-Visual Trials

As we were unsure if participants would change control strategies for the trials with feedback versus the trials without feedback for blocks 2 and 3, the data from these blocks were analyzed. We also observed whether or not the control strategies changed between the visual trials in Block 1 (consistent visual feedback) and the visual trials in Blocks 2 and 3 (visual feedback once every 4 trials).

A Friedman's ANOVA test was conducted on the percent simultaneity data. There were 3 groups for this test:

1. All data from block 1, where every trial had visual feedback
2. The visual trials only from blocks 2 and 3
3. The non-visual trials only from blocks 2 and 3.

Evidence was found that in Group 1 (no simultaneous noise), subjects did not change their percent of simultaneity in the absence of visual feedback when compared to the trials, where visual feedback was provided ($p = 0.355$) (Figure 20).

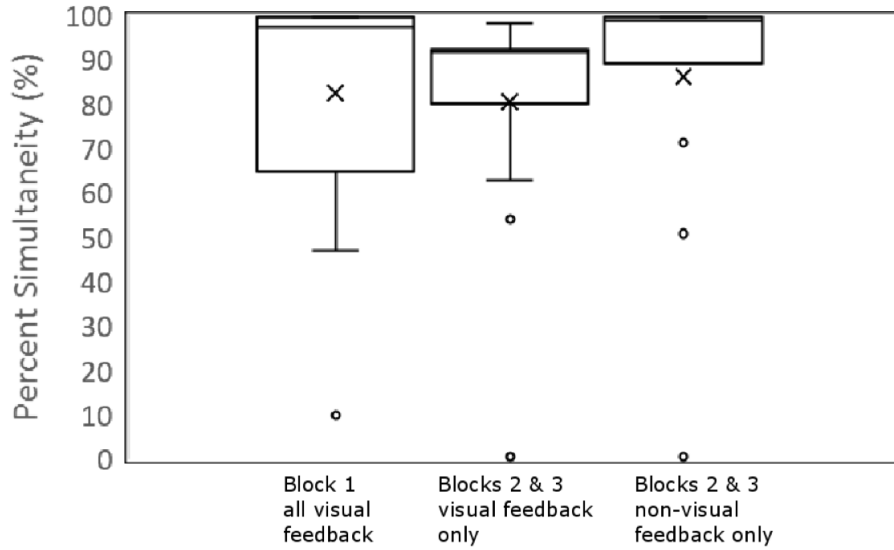


Figure 20: Box-plot of the Average Percent Simultaneity in Group 1

There was evidence that Group 2 (simultaneous noise) did not follow this same trend, and performed more simultaneously in the absence of feedback ($p < 0.05$). A statistical summary of the percent simultaneity for Group 1 and 2 in the absence and presence of visual feedback can be found in Table 5.

Table 5. Summary of Percent Simultaneity, Visual Feedback vs. No Visual Feedback

	Percent Simultaneity					
	Group 1			Group 2		
	Block 1 (All visual)	Block 2 & 3 (Visual Trials)	Block 2 & 3 (Non-Visual Trials)	Block 1 (All visual)	Block 2 & 3 (Visual Trials)	Block 2 & 3 (Non-Visual Trials)
Mean	82.49	80.59	86.25	63.12	64.09	70.67
Median	97.31	91.67	98.83	94.81	69.04	95.94
[25th -75th]	[69.17-99.56]	[85.93-92.38]	[95.20-99.54]	[21.25-97.8]	[43.22-84.28]	[45.81-99.11]
SD	27.79	26.19	28.44	43.19	25.07	41.13

A Wilcoxon signed-ranks test was performed for pairwise comparison on the results of the Friedman's ANOVA for Group 2. Evidence was found that subjects in Group 2 used more simultaneous control input in their non-visual trials when compared to the visual trials from Block 1 ($p < 0.05$) and the visual trials from Blocks 2 and 3 ($p < 0.05$). This means that participants that were subjected to simultaneous noise were more simultaneous (used less discrete movement) when they could not see the task that they were completing (Figure 21).

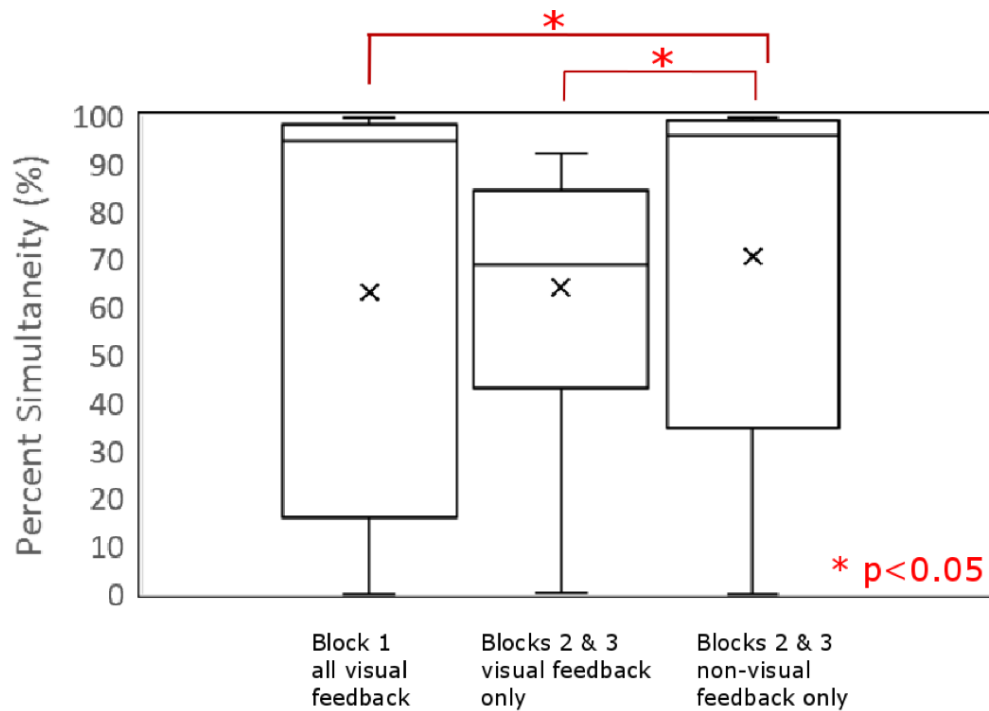


Figure 21: Box-plot of the Average Percent Simultaneity in Group 2

4.3 EXPERIMENTAL SUMMARY

Participants that were subjected to the simultaneous noise term in their movement did not show evidence that they took longer to complete the task, or had more error in their endpoint accuracy than those without simultaneous noise. We found evidence that under conditions of simultaneous noise, participants were more simultaneous than those without the simultaneous noise term, but the number of submovements between Group 1 and 2 were the same. Participants subjected to simultaneous noise had a higher percentage of simultaneity in the absence of visual feedback. This is likely due to an increase in real-time corrections when humans have visual feedback of their movement.

Whereas the model was a continuous representation of a linear system, the experiment was designed with discrete control. In the model, different control strategies produced different costs, which allows for an optimal control strategy. Our experiment was discrete control, where unfortunately, different control strategies did not produce different costs. In light of this, we were not tailoring the cost function in order to bias one particular control strategy. The reason for designing the experiment in discrete control was that we were able to extract the cleanest control signal possible, which lead to less variability when analyzing our data.

5 DISCUSSION

The goal of this work was to create a model that was capable of evaluating whether or not multiplicative noise influences the degree of simultaneity of control, and to apply the findings of this model and test it on subjects to observe whether it changed their optimal control strategy.

Although we didn't have a definitive biological reasoning behind the addition of simultaneous noise, we predicted that an extension of the intuition described by Shadmehr would explain the results we observe in real-life data. We suggested cross-talk as a possible explanation for the origin of the noise term. Our question then evolved from biological (is there evidence for this noise term) to behavioral, which asks whether people would be able to figure out a feedforward strategy in which the optimal control is to use submovements, even if they are more difficult to use (Shadmehr & Mussa-Ivaldi, 2012).

Due to the difficulty of learning the optimal control strategy in such conditions, we ran the experiment on gamers who were motivated and experienced enough to discover the optimal control strategy in the limited time of the experiment. During the pilot study conducted on non-gamers, it was found that the task was too difficult for the participants to learn in the timeframe allotted. The non-gamers were not able to learn a control strategy that worked for them upon completion of the exploration and training phase. Some subjects were not even able to keep the rocket on the screen. We found that during the time that non-gamers required to learn the dynamics of the experiment and implement a control strategy that would keep them on the screen, the participants lost focus and were not motivated to continue. Gamers proved to be able to maintain focus, to learn the control

strategies within 3 minutes, while also being motivated to reach the highest score possible during the trials.

It is possible that by testing more subjects, the results of the number of submovements would be different between the group that was subjected to simultaneous multiplicative noise and the group that was not.

5.1 STRENGTHS AND WEAKNESSES OF STUDY

The emergence of submovements in our model is not an artifact of coupling two systems together. One could argue that coupling two second order systems would produce a fourth order system which inherently created submovements (Nise, 2015). However, we modeled every combination of pole and zero placements for a fourth order system to check this phenomenon, and each case did not produce submovements.

The results of the model produced submovements in the velocity profile of the movement over a noise range of 5×10^{-11} and 25×10^{-11} for κ_{sx} and κ_{sy} . For noise values larger than 25×10^{-11} , the results became unpredictable and no longer followed the expected trends, e.g. velocity profiles grew significantly larger than feasible.

A television's refresh rate is typically 60Hz, however for a simple game, our refresh rate of 33Hz was adequate as refresh rates in slow or static scenes are rarely perceived above 30Hz.

Our results support the minimum-variance theory (Harris & Wolpert, 1998), in that the optimal control strategy is to move more at the beginning of a movement than at the end, in order to minimize a cost function. This was shown in the emergence of the submovements, where the largest submovement occurred at the beginning of the trial. However, our findings challenge existing literature, as our model predicts that

submovements may emerge even in the absence of feedback. Some models suggest that submovements are caused by feedback, and without feedback, the optimal control strategy is not to produce submovements (Woodworth, 1899). Our research suggests that there is a potential alternative explanation for some systems of dynamics. We found that for a particular set of dynamics which has been previously used to describe human movement in 1-DOF, we are able to predict the emergence of submovements in the presence of simultaneous multiplicative noise, even in the absence of visual feedback.

5.2 FUTURE WORK

Future experiments could be conducted on prosthesis-wearers to analyze how they control two joints at the same time (in cases where it is possible for simultaneous control of both joints). Future research could explore creating a model which predicts human behavior in more than 2-DOF, as this would align better with real-life human movement.

Different methods of training could be used for this study, as well as the set-up of the experiment. The experiment could be re-done in virtual reality to simulate more realistic human movement. Learning rates and strategies could be observed, particularly as subjects are first introduced to the experiment (exploration phase), by observing the patterns of control strategy choice that occurs during the initial task trials. It would also be interesting to observe the control strategy that subjects end up choosing when they receive no training at all.

As we found that running the experiment with simulated control signals produced approximately the same score for all four control signal options, it is possible that the subjects did not rely on the score bar, and simply used the clock and the endpoint accuracy as feedback for their success of the trial. As our score bar did not favor any control strategy

over the other, it would be interesting to weight the score bar towards the control strategy which performed simultaneous at the beginning and then switched to sequential movement at the end, and analyze whether the participants control strategy changed.

In future research, it would be useful to evaluate why the noise range was constrained in the model, and why it was constrained to a certain level of noise. It would also be useful to explore the potential biological reasoning behind the simultaneous noise term. The simultaneous noise term could potentially be caused by cross-talk, which occurs while operating 2-DOF simultaneously, however, more research is required in order to confirm this relationship.

6 CONCLUSION

The goal of this study was to further our understanding of the stereotypical characteristics of human movement in order to better inform rehabilitation practices. This was achieved by building upon an existing model, and adding new simultaneous noise terms κ_{Sx} and κ_{Sy} to observe their effects. We found that the inclusion of these noise terms allowed for the explanation of previously observed motor phenomena including the presence of submovements in multi-DOF tasks, and the transition from simultaneous to sequential control of joints.

As shown by Harris and Wolpert (1998), when we combine dissipative dynamics with multiplicative noise that grows with the control signal, asymmetric velocity profiles emerge in 1-DOF tasks. This is a powerful idea as it demonstrates how multiplicative noise affects the cost function and encourages the user to produce larger movements at the beginning of a task rather than at the end. However, most human movement is not constrained to 1-DOF, and an extension of this model provides a more sophisticated understanding of human motor control.

By extending the model to 2-DOF and including simultaneous multiplicative noise terms, we are able to explain previously observed motor phenomena including the presence of submovements in multi-DOF tasks, and the transition from simultaneous to sequential control of joints. This study is relevant because previous research was only able to explain submovements in the presence of visual feedback (Dipietro et al., 2009). As certain diseases such as schizophrenia and Parkinson's disease affect how the brain processes cost functions, this model can be used as a guide for healthy human motor control (Lindner et

al., 2005; Shadmehr & Mussa-Ivaldi, 2012). It can also be useful to compare to the movements of patients receiving rehabilitation in an effort to improve their motor planning (Dipietro et al., 2009; Rohrer et al., 2004). By using this template, we are able to run studies on patients with motor disorders and pinpoint how motor disorders affect movement planning. We can also explore whether the motor disorder increases the level of simultaneous noise in the patient's movement.

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APPENDIX A – Mathematical Expansion

This mathematical derivation expands Shadmehr's work in *Biological Learning and Control*, which incorporates multiplicative noise terms κ_x and κ_y into a 1-DOF movement in order to explain the asymmetry observed in the velocity profile of the task (R Shadmehr & Mussa-Ivaldi, 2012). Here, we add multiplicative simultaneous noise terms κ_{Sx} and κ_{Sy} into the expected value of the task. These added noise terms are dependent on how simultaneous we are during a 2-DOF movement.

The objective of a control policy is to minimize a cost function, J . When we take the expected value of a variance squared, it adds an offset to the optimal control law. This can be seen in (14), with the added value of the trace on the end.

$$E[x^T Ax] = E[x]^T AE[x] + tr[Avar[x]] \quad (14)$$

The expected values of the cost functions for the x-DOF and y-DOF are as follows:

$$E[J_x] = (F\Gamma\mathbf{u}_x)^T C^T T C F \Gamma \mathbf{u}_x + \kappa_x^2 \mathbf{u}_x^T S \mathbf{u}_x + \kappa_{Sx} \mathbf{u}_x^T S \mathbf{u}_y - 2(F\Gamma\mathbf{u}_x)^T C^T T \mathbf{r} + \mathbf{r}^T T \mathbf{r} + \mathbf{u}_x^T L \mathbf{u}_x \quad (15)$$

$$E[J_y] = (F\Gamma\mathbf{u}_y)^T C^T T C F \Gamma \mathbf{u}_y + \kappa_y^2 \mathbf{u}_y^T S \mathbf{u}_y + \kappa_{Sy} \mathbf{u}_y^T S \mathbf{u}_x - 2(F\Gamma\mathbf{u}_y)^T C^T T \mathbf{r} + \mathbf{r}^T T \mathbf{r} + \mathbf{u}_y^T L \mathbf{u}_y \quad (16)$$

$$E[J] = E[J_x] + E[J_y] \quad (17)$$

Simplify the equations by expanding the transposes,

$$E[J_x] = \mathbf{u}_x^T \Gamma^T F^T C^T T C F \Gamma \mathbf{u}_x + \kappa_x^2 \mathbf{u}_x^T S \mathbf{u}_x + \kappa_{Sx} \mathbf{u}_x^T S \mathbf{u}_y - 2 \mathbf{u}_x^T \Gamma^T F^T C^T T \mathbf{r} + \mathbf{r}^T T \mathbf{r} + \mathbf{u}_x^T L \mathbf{u}_x \quad (18)$$

$$E[J_y] = \mathbf{u}_y^T \Gamma^T F^T C^T T C F \Gamma \mathbf{u}_y + \kappa_y^2 \mathbf{u}_y^T S \mathbf{u}_y + \kappa_{Sy} \mathbf{u}_y^T S \mathbf{u}_x - 2 \mathbf{u}_y^T \Gamma^T F^T C^T T \mathbf{r} + \mathbf{r}^T T \mathbf{r} + \mathbf{u}_y^T L \mathbf{u}_y \quad (19)$$

The derivative is taken to find the minimum of the cost function and to evaluate it at zero.

$$\frac{dE}{d\mathbf{u}_x} = 2\Gamma^T F^T C^T T C F \Gamma \mathbf{u}_x + 2\kappa_x^2 S \mathbf{u}_x + \kappa_{Sx} S \mathbf{u}_y - 2\Gamma^T F^T C^T T \mathbf{r} + 2L \mathbf{u}_x + \kappa_{Sx} S \mathbf{u}_y^T \quad (20)$$

$$\frac{dE}{d\mathbf{u}_y} = 2\Gamma^T F^T C^T T C F \Gamma \mathbf{u}_y + 2\kappa_y^2 S \mathbf{u}_y + \kappa_{Sy} S \mathbf{u}_x - 2\Gamma^T F^T C^T T \mathbf{r} + 2L \mathbf{u}_y + \kappa_{Sy} S \mathbf{u}_x^T \quad (21)$$

Set equations (18) and (19) to 0 and solve.

$$(2\Gamma^T F^T C^T T C F \Gamma + 2\kappa_x^2 S + 2L) \mathbf{u}_x + 2\kappa_{Sx} S \mathbf{u}_y = 2\Gamma^T F^T C^T T \mathbf{r} \quad (22)$$

$$(2\Gamma^T F^T C^T T C F \Gamma + 2\kappa_y^2 S + 2L) \mathbf{u}_y + 2\kappa_{Sy} S \mathbf{u}_x = 2\Gamma^T F^T C^T T \mathbf{r} \quad (23)$$

Divide by 2, and block the following terms for simplicity's sake.

$$A \mathbf{u}_x + B \mathbf{u}_y = C \quad (24)$$

$$D \mathbf{u}_x + E \mathbf{u}_y = C \quad (25)$$

where

$$A = \Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L$$

$$B = \kappa_{Sx} S$$

$$C = \Gamma^T F^T C^T \mathbf{r}$$

$$D = \kappa_{Sy} S$$

$$E = \Gamma^T F^T C^T T C F \Gamma + \kappa_y^2 S + L$$

Solve for \mathbf{u}_x and \mathbf{u}_y

$$\mathbf{u}_x = \frac{C^T(A - D)}{-(BD - AE)} \quad (26)$$

$$\mathbf{u}_y = \frac{C^T(B - E)}{BD - AE} \quad (27)$$

Therefore, substituting our blocked terms we obtain:

$$\mathbf{u}_x = \frac{\Gamma^T F^T C^T \mathbf{r} [\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L - \kappa_{Sy} S]}{(\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L)(\Gamma^T F^T C^T T C F \Gamma + \kappa_y^2 S + L) - S^2 \kappa_{Sx} \kappa_{Sy}}, \quad (28)$$

$$\mathbf{u}_y = \frac{\Gamma^T F^T C^T \mathbf{r} [\kappa_{Sx} S - \Gamma^T F^T C^T T C F \Gamma - \kappa_y^2 S - L]}{S^2 \kappa_{Sx} \kappa_{Sy} - (\Gamma^T F^T C^T T C F \Gamma + \kappa_x^2 S + L)(\Gamma^T F^T C^T T C F \Gamma + \kappa_y^2 S + L)}. \quad (29)$$

These are the optimal control input for the X-DOF and Y-DOF of the task.

APPENDIX B – Experimental Code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%   November 22nd, 2017
%   Author: Katie Wilson
%
%   Description: This code runs a rocket game, where the user can use the
%   up and right arrows to control a target. The user can only move forward.
%   Multiplicative noise is present in all 3 cases (up, over, up+over).
%   Simultaneous noise can be set to be present in the up+over case by
%   setting the sim_noise parameter. After the "visualnum" trials are over,
%   visual feedback is only provided once every 3 trials. Endpoint feedback
%   is always shown. Positive/negative feedback is shown after every trial,
%   as well as a score after every individual trial, and a total cumulative
%   score. Score is based off of time taken to complete the trial, and the
%   endpoint error.
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc;
clear;
close all;

prompt = 'Enter Astronaut ID:\n';
id = input(prompt,'s');
%% Changeable parameters
visualnum =15;
trialendnum = 3*visualnum; % number of total trials
trialnum = 1; % initialize the trial number
trialflag=1; % initialize the trial flag, which will tell you if the trial should
get visual feedback or not
pictureflag = 0;
cutofftime = 5; % cut off time, if they take longer than this, the trial ends
enddwell = 0.5; % if they dwell for this amount of time, the trial ends
speedvar = 0.001; %The variable that gets multiplied by the counter variables, which sets
the speed of the rocket

i = 1;
n2=1;
cumscore = 0; % initialize the cumulative score to 0
n = 10000; % allocate space to check the refresh rate for each frame
toc = 0;

noise_x = 0; % set the noise to zero (this is only for debugging purposes)
noise_y = 0;
mult_noise = 0.006; % set the gain for the multiplicative noise
sim_noise = 0.01;% set the gain for the simultaneous noise
mult_noise = 0;% set the multiplicative noise, which is present in all 3 cases (up,
over, or over+up)
sim_noise = 0; % set the simultaneous noise, which is present only for the over+up case

%% Pre-allocate space for variables
mult_noise1 = randn (500,trialendnum)*mult_noise; % generating the random gaussian noise,
which will get multiplied by the gains
mult_noise2 = randn (500,trialendnum)*mult_noise;
sim_noise1 = randn (500,trialendnum)*sim_noise;
sim_noise2 = randn (500,trialendnum)*sim_noise;
cycle_time_unregulated = zeros(trialendnum,n); % allocating space for the cycle time,
which stores the refresh rate of the figure each time its generated
cycle_time_regulated = zeros(trialendnum,n); % allocating space for the cycle time after
it has been hard set, after looking at the unregulated refresh and taking the max
endtime = zeros(trialendnum,1);

for index = 1:1:trialendnum
    X_pos{index,:} = {zeros(500,1)}; % allocating space for the x position vectors to be
stored
```

```

    Y_pos{index,:} = {zeros(500,1)}; % allocating space for the y position vectors to be
stored
    controlsave_x{index,1} = {zeros(500,1)}; % allocating space for the x control signal
to be stored
    controlsave_y{index,1} = {zeros(500,1)}; % allocating space for the y control signal
to be stored
end

%% Set up figure/plotting properties
figure_handle = figure(1);
set(figure_handle, 'menubar', 'none', 'numbertitle', 'off', 'name', 'Astronaut Testing
screen', 'Renderer', 'OpenGL');
set(figure_handle, 'color', [1 1 1]); % set background color: [1 1 1] is white, [0 0 0]
is black
set(figure_handle, 'units', 'pixels', 'Position', [1 1 1920 1080]); % set figure to fill
window

axislimits = [-0.1 1.3 -0.3 0.6]; % specify
axes limits to frame reaches from x=0 to x=1
axis(axislimits); % set axes
limits
axis equal; % Make circles look like circles, not
ellipses
axis manual; % Make axes
permenent
axis off; % Don't
display axes
q=gca;
set(q, 'OuterPosition', [-.22 -.3 1.42 1.5]); % Get rid of the figure
borders

%**Speed up animation**
set(figure_handle, 'BackingStore', 'off', 'Interruptible', 'off')
set(figure_handle, 'KeyPressFcn', 'myKeyPressFcn');
axes_handle=gca;
set(axes_handle, 'DrawMode', 'fast');

rectangle('Position', [1.1, -0.1, 0.05, 0.6], 'FaceColor', 'w', 'EdgeColor', 'k', ...
'LineWidth', 3);
handles.rectangle =rectangle('Position', [1.1, -0.1, 0.05, 0.6], 'FaceColor', 'w');

% Info for moon
handles.moon = axes('position', [.4 .65 .5 .05]);
moon_img = imread('moon2.png');
image(moon_img);
axis off
axis image
% Info for rocket
handles.rocket = axes('position', [-0.2 0.05 .5 .05]);
rocket_none = imread('nothrust.png');
handles.rocket_ref=imshow(rocket_none, 'parent', handles.rocket);
% Info for moving rocket
blankrocket = imread('blankrocket.png');
% Info for astronaut
handles.astronaut = axes('position', [-0.2 0.05 .5 .05]);
set(handles.astronaut, 'visible', 'off');
axis off
axis image
rocketPos = get(handles.rocket, 'Position');
visual = strcat('Testing Phase - Visual Feedback'); % String to put in the textbox for
visual feedback trials
novisual = strcat('Testing Phase - No Visual Feedback'); % String to put in the textbox
for visual feedback trials
drawnow();
rocket_ref_none=imshow(rocket_none, 'parent', handles.rocket);

```



```

%% Loop which runs through the trials until the last trial is over

while trialnum<=trialendnum %Run this loop until the trial number is equal to the end
trial number

    n2 = 1;
    controlsig_y = zeros(500,1);          % Allocating space for storing the x control
signal for every trial
    controlsig_x = zeros(500,1); % Allocating space for storing the y control signal for
every trial
    rocketPosition = zeros(500,4);      % Allocating space for storing the rocket position
for every trial

    if trialnum<visualnum          % If the current trial number is less than the number of
visual trials, set the condition number to 1
        condnumber=1;
        trialflag = 0;          % Set the trial flag equal to zero to reset the counter of
3 for the "no visual feedback trials"

        elseif trialnum>= visualnum      % If the trial number is greater or equal to the
visual trial number, start the trials where its 1 visual feedback, 2 no visual.
            condnumber=2;      % Set the condition number to 2 (which means it shouldn't get
visual feedback)
            trialflag=trialflag+1;      % Increment the trial flag counter
            if trialflag>4          % If the trial flag is greater than 3, reset the
counter (go back to 1, where they will receive visual feedback)
                trialflag=0;
            end
        end

        [secs, q, keyCode] = KbCheck([],[],[]);          % Scan the
keyboard

        while keyCode(38)==0 && keyCode(39)==0          % If
either arrow key is being pressed, go into this loop (this is so the trial only starts
when the user starts moving)
            pause(0.1)
            [secs, q, keyCode] = KbCheck([],[],[]);
        end
        set(handles.rectangle,'Position',[1.1,-0.1,0.05,0.6],'FaceColor','w');
        set(handles.astronaut,'visible','off');          % Set the astronaut
picture off (until end of trial)

        tic;          % Start timer
        s5 = GetSecs;
        count = 0;          % Set the velocity control counters to zero
        count1 = 0;
        count2 = 0;
        dwellOnTarget = 0;          % Reset the dwell time
        startDwellTime = 0;          % Set the start of dwell time to
zero

        if condnumber==2 && trialflag >=1      % If youre in the second section of the
experiment (1 trial with feedback, 2 without) and if you're on either trial 2 or 3 in
this, take away visual feedback
            handles.rocket_ref=imshow(blankrocket, 'parent', handles.rocket); % Show a blank
rocket ( a white square, effectively no visual feedback)
        else
            handles.rocket_ref=imshow(rocket_none, 'parent', handles.rocket); % If you dont
meet those two conditions, then show visual feedback
        end
        starttime = GetSecs;
        trialttime = 0;
        % Real-time loop
        s = GetSecs;
        while trialttime<=cutofftime;          % Get the current time from Psych toolbox
% While the trial time hasn't surpassed the end cut
off time
            s3=GetSecs;
            WaitSecs('UntilTime', s+.02);

```

```

s= GetSecs; % Get the current time from Psych toolbox
[secs, q, keyCode] = KbCheck([],[],[]); % Scan the keyboard
if keyCode(38)==0 && keyCode(39)==0 % If neither key is being pressed, enter
this loop
    set (handles.astronaut, 'visible', 'off');

    noise_x = 0; % The noise is 0 if no key is being pressed
    noise_y = 0;
    count = count-0.35; % Decrement the velocity control counters if no key is
being pressed (slowing down)
    count1 = count1-0.35;
    controlsig_x(i) = 0; % The control signal for x and y are 0 if no key is being
pressed
    controlsig_y(i) = 0;
    if count<0 % If the velocity counter is negative, make a
floor at 0
        count=0;
    end

    if count1<0
        count1=0;
    end

    if flag == 0 % Set the start time to the clock if the flag is 0 (if they
aren't dwelling)
        startDwellTime = clock;
        flag = 1; % Set the flag equal to 1 so we know the dwelling has started

    end

    if length(startDwellTime)>1 % Not sure why, but it only works if done
like this
        dwellOnTarget = etime(clock,startDwellTime);
    else
        dwellOnTarget = 0;
    end

    if (dwellOnTarget>enddwell) % If the current dwell time is greater than the
cutoff dwell time, then break the trial
        break
    end
    else
    if keyCode(38)==1 % Case for up
        controlsig_y(i) = 1;
        count = count+0.35; % Increment the y velocity
counter
        flag = 0; % Reset the flag to zero (not dwelling)

        if keyCode(39)==1 % Case for up and over. Both pressed keys are
pressed
            noise_x = mult_noise1(i,trialnum) + sim_noise1(i,trialnum);
% Add both multiplicative and simultaneous noise to x
            noise_y = mult_noise2(i,trialnum) + sim_noise2(i,trialnum);
% Add both multiplicative and simultaneous noise to y
            count1 = count1+0.35; % Increment the x counter
            controlsig_x(i) = 1; % The control signal for x is 1
            % Only going up
        else
            noise_y = mult_noise2(i,trialnum);
            count1 = count1-0.35;
            if count1<0
                count1=0;
            end
            controlsig_x(i) = 0;
            noise_x = 0;
        end
    end
end
end

```

```

        if keyCode(39)==1 && keyCode(38)==0 % Case for over
            controlsig_x(i) = 1; % Control signal
for x is 1
            controlsig_y(i) = 0; % Control signal for y is 0
            count1= count1+0.35; % Increment the velocity counter for x
            count= count-0.35; % Decrement the velocity counter for y (slow this
dimension down)
            if count<0 % Creating a floor for if the counter is ever
negative
                count=0;
            end

            flag = 0; % Flag stating
that the user isn't dwelling
            noise_x = mult_noisel(i,trialnum); % The
noise in the x is only multiplicative

        end

        rocketPos = rocketPos + [(speedvar*count1) (speedvar*count) 0 0] + [noise_x
noise_y 0 0]; % Add the noise to the rocket's position state

        set(handles.rocket, 'Position', rocketPos); % Set the rockets
position to the handle
        rocketPosition(i,:) = rocketPos; % Incrementing
the storage for the next trial for rocket position

        drawnow(); % This is where
the picture gets drawn again

        s2 = GetSecs; % Basically, tic
        cycle_time_unregulated(trialnum,i) = s2-s; % Calculating the refresh time between
figure updates
        cycle_time_regulated(trialnum,i) = s2-s3;
        i = i+1; % Increment the counter for the noise
        timeelapsed = GetSecs;
        trialtime = timeelapsed-starttime;
    end

    clear dwellOnTarget;
    s4 = GetSecs;
    endtime(trialnum)=s4-s5; % Saving the end time

    endpoint_x = rocketPosition(i-1,1); % Save the x endpoint position for the score
calculation
    endpoint_y = rocketPosition(i-1,2); % Save the x endpoint position for the score
calculation
    endscore = (abs(((cutofftime)-enddwell)-(endtime(trialnum)-enddwell))/(cutofftime-
enddwell)) * 20); % Calculating the score for the length of time
    endpointerror_x = 40-(abs(.4 - endpoint_x)/.4 * 40); % Calculating end
point error of x-axis
    endpointerror_y = 40-(abs(.65 - endpoint_y)/.65 * 40); % Calculating end
point error of y-axis

    if endpointerror_x < 0 % If its a
negative error, round up to 0 (probably need to fix this.. why is it ever negative? - KW)
        endpointerror_x = 0;
    end

    if endpointerror_y<0;
        endpointerror_y=0;
    end

    handles.rocket_ref=imshow(rocket_none, 'parent', handles.rocket);
    drawnow();
    pause(0.3)

```

```

score = round(endscore + endpointerror_x + endpointerror_y);           % Total score,
time + endpoint_x + endpoint_y

handles.rocket_ref=imshow(rocket_none, 'parent', handles.rocket);
drawnow();
pause(1)
set(handles.rocket, 'Position',[-0.2 0.05 .5 .05]);                   % Setting the
rocket position back to original position
length_size = 0.6*score/100;
set(figure_handle,'color',[1 1 1]);
set(handles.rectangle,'Position',[1.1,-0.1,0.05,length_size],'FaceColor',[0 .5 .5]);
time = strcat('Time: ', num2str(round((endtime(trialnum)*10)/10)));
timePrompt = annotation('textbox', [0.73 0.1,0.1,0.1],...
    'String', time,'Color','k', 'BackgroundColor','w','visible','on','FontSize',25);
handles.rocket_ref=imshow(rocket_none, 'parent', handles.rocket);
drawnow();
pause(0.2);
rocketPos = [-0.2 0.05 .5 .05];                                       % Putting rocket back to starting
position at the end of the trial
set(handles.rocket, 'Position',[-0.2 0.05 .5 .05]);
drawnow();                     % Drawing the rocket at the start position

X_pos{trialnum,:} = rocketPosition(:,1); % Saving x rocket position in cell of X_pos
which will be saved later
Y_pos{trialnum,:} = rocketPosition(:,2); % Saving y rocket position in cell of Y_pos
which will be saved later
controlsave_x{trialnum,:} = controlsig_x(:,1);                         % Saving control signal
controlsave_y{trialnum,:} = controlsig_y(:,1);                         % Saving control signal

clear rocketPosition                                                  % Clearing variables
clear controlsig_x
clear controlsig_y
trialnum = trialnum + 1;                                             % Increment the trial
number
i=1;
end
s1_toc = GetSecs;                                                    % Basically, toc
%% Incrementing trial number
if trialnum == trialendnum;                                         % If number of trials is the end number, close the
figure
close all;
end
%% Saving the control signals and the position trajectory
data.controlsig_x = controlsave_x;
data.controlsig_y = controlsave_y;
data.X_pos = X_pos;
data.Y_pos = Y_pos;
data.id = id;
str = date;
scoreval = strcat(num2str(id),'_Subject_',num2str(str));
save(scoreval,'-struct','data');                                     % Save data

```

APPENDIX C – Consent Form

Research Consent Form

University of New Brunswick
Institute of Biomedical Engineering
Fredericton NB

Project Title: Modeling, Quantification, and Optimization of Prosthesis-User Interface

Principle Investigator: Jonathon W. Sensinger, PhD

This project has been reviewed by the Research Ethics Board of the University of New Brunswick and is on file as REB 2014-019

PURPOSE

You are being asked to participate in a research study on the way people move. The purpose of this study is to determine how uncertainty affects movement. Your participation in this study is completely voluntary. Data collected from this experiment will be used to help design future devices.

STUDY CONTACTS

You may contact Dr. Sensinger by telephone between 9am-4pm, Monday through Friday, at (506) 458-7094. If you have questions or concerns and wish to talk with someone not associated with this study, you may either contact Dr. McGibbon within the Institute of Biomedical Engineering at 506-458-7098, or Dr. Turner, the Research Ethics Board chair, at 506 458 7433.

PROCEDURES

As a subject in this study, you will be asked to come to the Institute of Biomedical Engineering (IBME) at the University of New Brunswick. Your part in this study will last for up to 3 hours per visit, may involve up to 5 visits per task, and may involve up to 4 tasks (for a total of 20 visits).

You will move and we will measure aspects of your movements. You will press buttons, rotate knobs or move in 3 dimensional space. While you move, sensors will measure how you move or the forces you produce while moving. Moreover, your hand may be attached to the end of a robotic manipulator that will produce weak forces onto your hand, and self-adhesive electrodes may be placed on your arm.

If you give permission in the “Optional Study Elements” below, you may be photographed or videotaped. These photographs and videos will not include your face. You may still participate in this study if you choose not to have your photo or video taken.

COSTS

There is no cost to you for participating in the study.

If you are traveling from out of town, you will be reimbursed for your travel (\$0.41/km) and appropriate meals (\$9.50 for breakfast, \$11.50 for lunch, and \$24.00 for dinner).

RISKS AND DISCOMFORTS

There should be no risk or discomfort with these studies beyond those normally experienced when playing video games or attaching adhesive to your skin. Your participation in this study may involve the following risks:

- Muscle soreness from movement.
- The adhesive used to hold the electrodes in place may produce minor irritation of the skin. The possibility of irritation will be minimized by cleaning the skin with alcohol before and after placement of the electrodes.

BENEFITS

There may be no direct benefit to you by your participation in this research study. However, your participation may aid in our understanding of human movement, which may be helpful for better rehabilitation in the future.

PRIVACY AND CONFIDENTIALITY

All personal information gathered for this study that identifies participants will be kept secure to protect their privacy. Data collected during the study and shared with others will identify participants only by a coded number. The “master list” linking personal information to the coded number will not be shared, and will be kept in a separate, locked cabinet at the IBME.

Information gathered from participants will be used and shared with others for research purposes only. These “others” could include researchers at UNB (faculty and graduate students), and the UNB Research Ethics Board. They are required to keep your personal information confidential.

Statement of privacy rights:

You have the right to withdraw your permission for the researchers to use or share your protected health information. We will not be able to withdraw all of the information that already has been used or shared with others. Your personal information will never be shared at any time with any person or entity. If you withdraw your permission, you cannot participate further in the research. If you want to withdraw your permission, you must do so by informing the Study Contact.

- You do not have to sign this form. If you decide not to sign, you cannot participate in this research study. Refusing to sign will not affect your present or future care. Refusing to sign will not cause any penalty or loss of benefits to which you are otherwise entitled.
- You have the right to disallow use of your data in future studies, related or unrelated to this project. If you want to disallow use of your data in future studies, you must do so by informing the Study Contact.

PUBLICATION OF RESULTS OR USE FOR TEACHING PURPOSES

The results of this study may be published in a medical book or journal or used for teaching purposes. Your name or other identifiers will not be used in any publication or teaching materials without your specific permission.

You are encouraged to visit our website (www.unb.ca/biomed), which lists publications based on deidentified results of this research.

REQUEST FOR MORE INFORMATION

You may ask more questions about the study at any time. The researcher(s) will provide their telephone number so that they are available to answer your questions or concerns about the study. A copy of this consent form will be given to you to keep.

If you want to speak with someone not directly involved in the study about your rights as a research subject, your participation in the study, any concerns you may have about the study, or a research-related injury, contact the UNB Research Ethics Board at (506) 453-5189. You can also contact them if you feel under any pressure to enroll or continue to participate in this study.

REFUSAL OR WITHDRAWAL OF PARTICIPATION

Participation in this study is voluntary. You can refuse to participate or drop out of the study at any time without penalty or loss of benefits. Refusing to participate or dropping out of the study will not affect your present or future care by the doctors or the participating hospitals. The investigator in charge of this study may decide to end your participation in this study at any time if it is in your best medical interests and will explain the reasons for doing so.

INJURY STATEMENT

All injuries should be reported no matter how minor. The following procedures will be followed in the event you are injured during the course of the study and as a direct result of this study:

1. If an injury occurs during data collection in the presence of study staff the data collection will cease immediately and a trained staff member will seek medical assistance if required.
2. If an injury relating to the study occurs not in the presence of study staff (eg. delayed onset of muscle soreness) contact the Principle Investigator at the number provided under the Study Contacts section in this form.

An injury report can be made available to the appropriate authority if required. All reported injuries will be reviewed by the project Engineering and Medical staff, and used to revise data collection procedures or to modify equipment to prevent future injury.

Optional Study Elements:

Photography and/or Videotaping:

CONSENT TO PARTICIPATE IN RESEARCH AND AUTHORIZATION TO USE OR RELEASE INDIVIDUAL HEALTH INFORMATION FOR RESEARCH

I confirm that the purpose of the research, the study procedures, the possible risks and discomforts and potential benefits that I may experience have been explained to me. All my questions have been answered. I have read this consent form. My signature below indicates my willingness to participate in this research study and my authorization to use and share with the specified others my “protected health information” as described in the preceding paragraphs.

NAME (Please print):

SIGNATURE:

Subject

Date/Time

Subject’s preferred contact information during course of study:

If the subject is under 19 years of age:

NAME (Please print):

SIGNATURE:

Subject’s Parent or Legal Guardian

Date/Time

Relationship to Participant (Parent, Legal Guardian, etc..)

I have explained the purpose of the research, the study procedures, identifying those that are investigational, the possible risks and discomforts and potential benefits. I have answered any questions regarding the research study to the best of my ability.

Investigator/Individual Obtaining Consent

Date/Time

CURRICULUM VITAE

Kathleen Rose Wilson

University of New Brunswick (B.Sc. in Electrical Engineering, May 2015)

Conferences:

Wilson, K. R., Englehart, K. B., & Sensinger, J. W. (2017). The Effects of Control Signal Noise on Simultaneous Submovements, IEEE 15th International Conference on Rehabilitation Robotics. London, UK.

Publications:

Wilson, K. R., Englehart, K. B., & Sensinger, J. W. (2017). The Effects of Control Signal Noise on Simultaneous Submovements, IEEE 15th International Conference on Rehabilitation Robotics. London, UK. (Poster Presentation)

Wilson, K. R., Englehart, K. B., & Sensinger, J. W. (2016). The Effects of Control Signal Noise on Simultaneous Sub-movements, 8th Annual Health Research Conference, Fredericton, NB. (Poster Presentation)