Journal of Visualized Experiments

WheelCon: A wheel control-based gaming platform for studying human sensorimotor control

--Manuscript Draft--

Article Type:	Invited Methods Collection - Author Produced Video
Manuscript Number:	JoVE61092R2
Full Title:	WheelCon: A wheel control-based gaming platform for studying human sensorimotor control
Section/Category:	JoVE Neuroscience
Keywords:	Sensorimotor control, gaming platform, control theory, layered architecture
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Additional Information:	
Question	**Response**
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TITLE:

WheelCon: A Wheel Control-Based Gaming Platform for Studying Human Sensorimotor Control

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KEYWORDS:
Sensorimotor control, gaming platform, control theory, layered architecture

SUMMARY:
WheelCon is a novel, free and open-source platform to design video games that noninvasively simulates mountain biking down a steep, twisting, bumpy trail. It contains components presenting in human sensorimotor control (delay, quantization, noise, disturbance, and multiple feedback loops) and allows researchers to study the layered architecture in sensorimotor control.

ABSTRACT:
Feedback control theory has been extensively implemented to theoretically model human sensorimotor control. However, experimental platforms capable of manipulating important components of multiple feedback loops lack development. This paper describes WheelCon, an open-source platform aimed at resolving such insufficiencies. Using only a computer, a standard display, and inexpensive gaming steering wheel equipped with a force feedback motor, WheelCon safely simulates the canonical sensorimotor task of riding a mountain bike down a steep, twisting, bumpy trail. The platform provides flexibility, as will be demonstrated in the demos provided, so that researchers may manipulate the disturbances, delay, and quantization (data rate) in the layered feedback loops, including a high-level advanced plan layer and a low-level delayed reflex layer. In this paper, we illustrate WheelCon's graphical user interface (GUI), the input and output of existing demos, and how to design new games. In addition, we present the basic feedback model and the experimental results from the demo games, which align well with the model's prediction. The WheelCon platform can be downloaded at https://github.com/Doyle-Lab/WheelCon. In short, the platform is featured to be cheap, simple to use, and flexible to program for effective sensorimotor neuroscience research and control engineering education.

INTRODUCTION:

The human sensorimotor control system is extremely robust[1], although the sensing is distributed, variable, sparse, quantized, noisy and delayed[2–4]; the computing in the central nervous system is slow[5–7]; and the muscle actuation fatigues and saturates[8]. Many computational theoretical models have been proposed to explain the complicated human sensorimotor control process[4,9-14], which is a tradeoff process in human reach and response[15,16]. For example, feedback control theory predicts the optimal control policy[12], Bayesian theory models sensorimotor learning[17–19] and information theory sensorimotor foundation[20,21]. In contrast to the abundance of theoretical models, experimental platforms capable of manipulating important components of multiple feedback loops lack development. This is in part due to the fact that designing a platform to bridge and test these aspects of sensorimotor control requires a diverse range of expertise, extending from motor control theory, signal processing, and interaction, all the way to computer graphics and programming. Researchers often develop their own custom hardware/software systems to characterize human sensorimotor control performance, which can limit the ability to compare/contrast and integrate datasets across research groups. The development of an easy-to-use and validated system could broaden the quantitative characterization of sensorimotor control.

In this paper, we present the WheelCon platform, a novel, free and open-source platform to design video games for a virtual environment that noninvasively simulates a Fitts' Law reaching game and a mountain bike task with downing a steep, twisting and bumpy trail. The Fitts' law for reaching task quantifies the tradeoff between speed and accuracy in which the time required for reaching a target of width W at distance D scales as $\log_2(2D/W)$[22,23]. The 'mountain-bike task' is a combination of a pursuit and compensatory tracking task, which are two classic components of research on human sensorimotor performance, especially in terms of studying feedback loops.

WheelCon contains the highly demanded basic components presented in each theory: delay, quantization, noise, disturbance, and multiple feedback loops. It is a potential tool for studying the following diverse questions in human sensorimotor control:

- How the human sensorimotor system deals with the delay and quantization in neural signaling, which is fundamentally constrained by the limited resources (such as the space and metabolic costs) in the brain[24, 25];
- How neural correlation in the human cortex with sensorimotor control[26];
- How humans handle the unpredictable, external disturbances in sensorimotor control[27];
- How the hierarchical control loops layered and integrated within human sensorimotor system[16,28,29];
- The consequence of the delay and quantization in human visual feedback[30] and reflex feedback[31] in sensorimotor control;
- The optimal policy and strategy for sensorimotor learning under delay and quantization[16,17,24,29].

WheelCon integrates with a steering wheel and can simulate game conditions that manipulate the variables in these questions, such as signaling delay, quantization, noise, and disturbance, while recording the dynamic control policy and system errors. It also allows researchers to study the layered architecture in sensorimotor control. In the example of riding a mountain bike, two control layers are involved in this task: the high-layer plan and the low-layer reflex. For visible disturbances (i.e., the trail), we plan before the disturbance arrives. For disturbances unknown in advance (i.e., small bumps), the control relies on delayed reflexes. Feedback control theory proposes that effective layered architectures can integrate the higher layers' goals, plans, decisions with the lower layers' sensing, reflex, and action[24]. WheelCon provides experimental tools to induce distinctive disturbances in the plan and reflex layers separately for testing such a layered architecture (**Figure 1**).

We provide a cheap, easy to use and flexible to program platform, WheelCon that bridges the gap between theoretical and experimental studies on neuroscience. To be specific, it can be used for examining the effects of delay, quantization, disturbance, potentially speed-accuracy tradeoffs. The variables that can be manipulated in control loops are shown in **Table 1**. It can also be applied for studying decision making and multiplexing ability across different control layers in human sensorimotor control. Moreover, WheelCon is compatible with noninvasive neural recordings, such as electroencephalography (EEG), to measure the neural response during sensorimotor control[32–35], and the non-invasive brain stimulation techniques, such as Transcranial Electrical Stimulation (tES) and Transcranial Magnetic Stimulation (TMS), to manipulate the neural activity[36,37].

PROTOCOL:

The development and application of the protocol were approved by the California Institute of Technology Institutional Review Board (IRB) and the Southern University of Science and Technology IRB. The subject provided informed consent prior to any procedures being performed.

1. System preparation and setup

1.1. Use the recommended basic hardware requirements: 2 GHz dual-core processor and 4 GB of system memory.

1.2. Build the gaming platform under the Unity platform, while using C# programing language. The Logitech gaming wheel driver and Logitech Steering Wheel SDK are needed for gaming platform development.

1.3. The gaming platform executable files only support Windows 10 Operating System (OS). Therefore, on a PC running Windows 10, download and install the corresponding racing wheel driver. Then download the compressed WheelCon software (https://github.com/Doyle-Lab/WheelCon/archive/master.zip) and extract the files to the local hard drive.

1.4. Mount the racing wheel securely at the sitting level in front of a monitor, and then connect the wheel's USB cable to the PC and the power adapter to an outlet.

1.5. Start the driver GUI to test for correct input readout and force feedback. Importantly, keep the driver GUI running in the background during the test.

1.6. To start the program, double-click on **WheelCon.exe** in the '\WheelCon-master\Executable & Output Files\' directory.

1.7. On the configuration screen, choose settings for monitor and click **Play!** (**Figure 2a**). The main menu will appear. Make sure the display size and location are as specified.

NOTE: The 'Wheel Sensitivity' value, defining cursor speed, ranges from 0 to 1, and defaults to 0.5. In case the range of motion afforded by the racing wheel does not suit specific task parameters, adjust this value. For example, decrease the sensitivity for the aging population. However, for comparing between tasks, it is necessary to keep this value constant for the battery and across groups.

2. Task implementation

2.1. Fitts' law reaching game

NOTE: The Fitts' law reaching game simulates the reaching process. The subject requires to turn the wheel to place the vertical line into the desired region (**Figure 2d**).

2.1.1. Seat the subject comfortably behind the wheels. Adjust the wheel height if necessary.

2.1.2. On the main menu, click **Fitts' Law Task** (**Figure 2b**) and type in a name for the output file indicating subject identification and task information on the textbox.

2.1.3. Click on **Select File**, choose **t_path_fitts_law.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click **Begin Game**.

2.1.4. Instruct the subject to move the green vertical line with the wheel to place it within the gray zone. This task serves to familiarize the subject with maneuvering the wheel, as well as with the color convention used throughout different tasks.

2.2. Mountain bike tasks

NOTE: The mountain bike task is a combination of pursuit and compensatory tracking task. It simulates riding a mountain bike down a steep, twisted and bumpy trail. The subject can see the trail and turn the wheel to track it, while a motor can torque the wheel to mimic invisible bumps in the trial (**Figure 2e**).

2.2.1. Game 1: Testing the effect of the visual delay

NOTE: In this game, the length of the look-ahead window (advanced warning vs. delay) is manipulated.

2.2.1.1. On the main menu, click **Mountain Bike Task** (**Figure 2c**) and type in a name for the output file indicating subject identification and task information on the textbox.

2.2.1.2. Click on **Select File**, choose **Vision_Delay.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click on **Begin Game**.

2.2.1.3. Instruct the subject to move the green vertical line with the wheel in order to track the part of the gray trail that intersects the purple horizontal line.

2.2.2. **Game 2: Testing the effect of action delay**

NOTE: In this game, a delay of various lengths is added between wheel movement and action output.

2.2.2.1. On the main menu, click on **Mountain Bike Task** and type in a name for the output file indicating subject identification and task information on the textbox.

2.2.2.2. Click on **Select File**, choose **Action_Delay.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click **Begin Game**.

2.2.2.3. Instruct the subject to move the green vertical line with the wheel in order to track the part of the gray trail that intersects the purple horizontal line.

2.2.3. **Game 3: Testing the effect of visual quantization**

NOTE: In this game, visual input is quantized to limit the data rate.

2.2.3.1. On the main menu, click on **Mountain Bike Task** and type in a name for the output file indicating subject identification and task information on the textbox.

2.2.3.2. Click on **Select File**, choose **Vision Quantization.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click **Begin Game**.

2.2.3.3. Instruct the subject to move the green vertical line with the wheel in order to track the part of the gray trail that intersects the purple horizontal line.

2.2.4. **Game 4: Testing the effect of action quantization**

NOTE: In this game, action output is quantized to limit the data rate.

2.2.4.1. On the main menu, click on **Mountain Bike Task** and type in a name for the output file indicating subject identification and task information on the textbox.

2.2.4.2. Click on **Select File**, choose **Action Quantization.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click **Begin Game**.

2.2.4.3. Instruct the subject to move the green vertical line with the wheel in order to track the part of the gray trail that intersects the purple horizontal line.

2.2.5. **Game 5: Testing the effect of bump and trail disturbance**

NOTE: This task consists of three scenarios:
a) "Bumps", tracking a constant trail subject despite torque disturbances on the wheel that mimic hitting bumps when riding a mountain bike;
b) "Trail", tracking a moving trail with random turns but without bumps;
c) "Trail with Bumps", tracking a moving trail with random turns and bumps.

2.2.5.1 On the main menu, click on **Mountain Bike Task** and type in a name for the output file indicating subject identification and task information on the textbox.

2.2.5.2 Click on **Select File**, choose **Bump & Trail.txt** in the '\WheelCon-master\ Demo Input Files\' directory, and then click **Begin Game**.

2.2.5.3 Instruct the subject to move the green vertical line with the wheel in order to track the part of the gray trail that intersects the purple horizontal line.

3. Data output

3.1. Locate the TXT output file in the '\WheelCon-master\Executable & Output Files\MountainBikeData\' directory, and then open with Matlab' WheelCon Data Analysis Code.m' in the '\WheelCon-master\Source Code' directory.

3.2. Specify in the MATLAB script the *folder* and *file_names* variables according to the output file directory, and then run the script (Ctrl + Enter), and the output variables will be saved as column vectors to the Workspace. The error and control policy will be exported for each sampling time. See **Table 2** for the detailed description.

4. Input file development

4.1. Open 'WheelCon Mntn Bike Trail Design Code.m' in the '\WheelCon-master\Source Code\' directory.

4.2. Uncomment (Ctrl + T) the section for the desired game parameters and run the script (Ctrl + Enter). The input file will be saved in the '\WheelCon-master\Source Code\' directory' in .txt format. Each column in the input files is one control variable. Refer to **Table 1** for the list of control variables.

REPRESENTATIVE RESULTS:

Modelling Feedback Control

We show a simplified feedback control model shown in **Figure 1**. The system dynamics is given by:

$$x(t+1) = x(t) + u(t) + w(t) + r(t)$$

where $x(t)$ is the error at time t, $r(t)$ is the trail disturbance, $w(t)$ is the bump disturbance, and $u(t)$ is the control action.

Modeling Action Delay in Trail Disturbance

When there is a delay T in action, and a trail disturbance $r(t)$, we model the control action by

$$u(t+T) = \kappa\big(x(0{:}\,t), r(0{:}\,t), u(0{:}\,t+T-1)\big) \quad (1)$$

The game starts with zero initial condition: $x(0) = 0$. The controller κ generates the control command $u(t)$ using the full information on the histories of state, disturbance, and control input. Here, the net delay T is composed of the internal delays in the human sensorimotor feedback and the delays externally added. The control command is executed with delay $T \geq 0$. Sensorimotor control in the risk-aware setting motivates the use of L1 optimal control, and as such, the goal is to verify the following robust control problem

$$\inf_{\kappa} \sup_{\|r\|_\infty \leq 1} \|x\|_\infty \quad (2)$$

This problem admits a simple and intuitive solution. The optimal cost is given by

$$\inf_{\kappa} \sup_{\|r\|_\infty \leq 1} \|x\|_\infty = T \quad (3)$$

This optimal cost is achieved by the worst-case control policy $u(t+T) = -r(t)$, which yields

$$\inf_{\kappa} \sup_{\|r\|_\infty \leq 1} \|u\|_\infty = 1 \quad (4)$$

Modeling Action Quantization in Trail Disturbance

When the data rate, R, in the control loop is limited, the control action is generated by the following feedback loop with communication constraints,

$$u(t) = Q\big(\kappa_t\big(x(0{:}\,t), u(0{:}\,t-1)\big)\big) \quad (5)$$

where κ_t: $(\mathbb{R}^{t+1}, \mathbb{R}^t) \to \mathbb{R}$ is a controller, and Q: $\mathbb{R} \to S$ is a quantizer with data rate $R \geq 1$, i.e. S is a finite set of cardinality 2^R. The disturbance $r(t)$ is infinity-norm bound and without loss of generality, $\|r\|_\infty \leq 1$. The worst-case state deviation is lower-bounded by

$$\sup_{\|r\|_\infty \leq 1} \|x\|_\infty \geq \frac{1}{2^R - 1} \quad (6)$$

and the minimum control effort is given by

$$\sup_{\|r\|_\infty \leq 1} \|u\|_\infty \geq \left(1 + \frac{1}{2^R - 1}\right)\left(1 - \frac{1}{2^R}\right) \quad (7)$$

Measures of Error

To quantify the performance, we measured the infinity norm error ($\|x\|_{\infty}$), mean absolute error (MAE) and root mean square error (RMSE). The infinity norm is defined as the maximum of the absolute errors, where

$$\|x\|_{\infty} = max(|x(1)|, |x(2)|, \dots, |x(n)|) \tag{8}$$

Mean absolute error is calculated as follows

$$MAE = \frac{1}{n}\sum_{t=1}^{n}|x(t)| \tag{9}$$

Root mean squared error is calculated as follows

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}|x(t)|^2} \tag{10}$$

Game 1: Visual Advanced Warning or Delay

Game 1 evaluates how the length of the look-ahead window (advanced warning/delay) affects sensorimotor control performance without being exposed to additional disturbances.

Game 1 lasts for 360 seconds and consists of one continuous "Trail", which reduces the amount of look-ahead every 30 seconds. The game begins with 1 s of advanced warning, and then decreases to 0.75 s, and then to 0.5 s. From there, the game decreases the look ahead by 0.1 s until a minimum of -0.4 s is reached. Positive delay, or negative advanced warning, means only the trail behind the player is visible.

An evolution of error dynamics of the player as the game progresses with 1 s advanced warning and 0.4 s delay were depicted in **Figure 3a-3b** separately. Both the plot display only the middle 20 seconds of each of the 30-second intervals to neglect the effects of the player adjusting to the new look-ahead window. The progression of the error in the blocks looks stable in the 1 s advanced warning setting while in the 0.4s delay setting, the error flips upside down during the progress. To quantify that effect in more detail, we evaluate L1-/L2-/L_{∞}- norm for the error dynamics for every 20 s group corresponding to a delay level. Summarizing these calculations in a plot gives **Figure 3c**, which demonstrates how the players' error-norm does not change until the advanced warning reaches 0.5 s and then increases in an approximately linear fashion.

Game 2: Delay in Action Output

Unlike Game 1's external visual delay, Game 2 adds specific internal delay to the action output; in other words, the current control policy $u(t)$ works at $u(t + T_{act})$ where T_{act} is the external delay in action. Game 2 lasts for 180 s. Adjusting T_{act} every 30 s, T_{act} starts at 0 s, and increments by 0.1 s until it reaches 0.4 s.

The effects of delay in action are shown in **Figure 4**. Similar to the vision delay, the error increases linearly with the delay, which is well in line with the prediction from theory in Eq(3).

Game 3 and Game 4: Quantization in Vision input and Action Output

Game 3 and Game 4 study the effects of quantization in vision input and action output, respectively. Each game is 210 s long, and the quantization changes every 30 s, with the data rate increasing from 1 to 7 bits. For example, when the R_{vis} is 1 in Game 3, the desired position (gray line in the gaming GUI) is presented either in the center-left or the center-right of the screen. When R_{vis} = n, the desired position can be presented in 2^n possible locations on the screen. For Game 4, when R_{act} = 1, the player is either going left or right with one speed. When R_{act} is n, the player can steer the wheel to go left or right with 2^{n-1} speeds.

The effects of quantization (limited data rate) in the vision and action are shown in **Figure 5**. Consistent with the theory's prediction in Eq(6), sensorimotor control performance improves with higher data rates and reaches the optimal control performance when R is around 5.

Game 5: Bump and trail disturbance

Game 5 is designed to test the effects of bump and trail disturbances on human sensorimotor control. Game 5 consists of three scenarios:
a) "Bumps", tracking a constant trail subject despite torque disturbances on the wheel that mimic hitting bumps when riding a mountain bike;
b) "Trail", tracking a moving trail with random turns but without bumps;
c) "Trail with Bumps", tracking a moving trail with random turns and bumps.

Each scenario lasts for 60 s in the order (Bumps, Trail, Trail with Bumps) with a 5 s rest preceding each scenario. Furthermore, the disturbances and the trail during the isolated phases are duplicated in the combined "Trails with Bumps" phase, so that a proper performance comparison can be drawn between the separate tasks and the one where the player must multiplex. During the entire game, there is 1 s of advanced warning in vision input, no delay in action output, and a 10-bit data rate for both vision and action.

As the disturbance, we use a random, binary signal, whose amplitude is the maximum possible torque the motor of the steering wheel can exert. In every 100 ms, the torque switches between max positive and negative (100 or -100 for the wheel). A similar random binary switching controls the trail derivative. More specifically, the trail travels at a constant speed but randomly switches its direction such that it always stays in the screen range comfortably visible to the player. We adjusted the velocity of the trail on the screen such that the required steering wheel turning rate is approximately 75°/s. **Figure 6** illustrates the 5 s snapshots of the error dynamics for each scenario during the game.

NOTE: Since this is used to study the sensorimotor control performance with limits of delay and data rate, we only analyzed the data after the subjects were trained for the task, and their performance became stable. The learning effects have been excluded from the data. Moreover, the feedback control model has not considered learning.

FIGURE AND TABLE LEGENDS:

Figure 1: Basic block diagram for an experimental platform with subject and gaming wheel with a motor. Each box is a component that communicates or computes and has potentially both delay and quantization, including within the game in G. The advance warning T is also implemented on a computer screen with vision.

Figure 2: The user-graphic interface for WheelCon. (**a**) the main menu; (**b**) the Fitt's Law Task menu; (**c**) the Mountain Bike Task menu; (**d**) the video game interface for Fitt's Law Task; (**e**) the video game interface for Mountain Bike Task.

Figure 3: Adding delay in vision input during the mountain-bike task. (**a-b**) The system dynamics with time for the session with 1 s advanced warning (**a**) and with 0.4 s delay (**b**). The black line and blue line are the trail position and the player position, respectively. The red line is the error dynamics. (**c**) Error increases with the increasing delay. The negative delay means advanced warning.

Figure 4: Effects of external delay in action on performance. The L_∞ norm of error, MAE and RMSE increases with the increasing delay.

Figure 5: Quantization in vision input (a) and action output (b). The L_∞ error, MAE and RMSE are shown in the blue, black and red line, respectively.

Figure 6: Effects of bump and trail disturbance on human sensorimotor control. (**a**) the error dynamics induced by bump disturbance; (**b**) the error dynamics induced by trail disturbance; (**c**) the error dynamics induced by bump and trail disturbance; (**d**) the overlayed error in bumps (blue), trails (red), Trails with bumps (green). The purple-empty and orange-filled stem plots indicate the timing and direction of the bump disturbances and trail disturbance, respectively. Note that both the wheel forces and the trail rates are square waves, and the stems indicate where these square waves switch (i.e., derivatives of the forces and rates).

Table 1: The variables in control loops which can be manipulated.

Table 2: The state variable and input signal in the dynamic system.

Table 3: The list of some existing sensorimotor platform.

DISCUSSION:

In this paper, we have presented a free, open-source gaming platform, WheelCon, for studying the effects of delay, quantization, disturbance, and layered feedback loops in human sensorimotor control. We have shown the hardware, the software, and the GUI. The settings of a single sensorimotor control loop with delay and quantization have been implemented, which allows us to measure the effects of delay, quantization, and disturbance in sensorimotor control. The experimental results are well in line with the prediction from the feedback control theory.

The protocols provide a way to noninvasively manipulate external delays and limit the data rate in both vision inputs and action output, and to analyze the sensorimotor control performance. In the protocol, we ask the participants to play the game under several task scenarios that have been pre-defined in the platform. With these tasks, we verified the linear effect of delay (**Figure 3** and **Figure 4**) and the nonlinear effect of quantization (**Figure 5**). These effects imply the optimization given the speed-accuracy tradeoff in human sensorimotor control. The protocol also allows us to study the layered feedback loops in the human sensorimotor system with a high-level advanced plan layer and a low-level delayed reflex layer (**Figure 6**).

In this protocol, it is crucial to train, but not over train, the participant in advance; otherwise, the learning effects or the tiredness of participants will impact the predictions of the model. The variability of the sensorimotor ability across participants is inevitable, and therefore some parameters in the protocol (i.e., the wheel sensitivity and the torque of bump) need to be tuned based on participants' age, strength, and motor skills. Matching these parameters across groups is necessary. Here, we suggest that the user chooses an appropriate sensitivity for both the old and young group in order to make a comparison.

One limitation of the method is that the model presented here did not consider the learning process. It is important to note that we only analyzed the data after the subjects were well trained, and their performance became stable to avoid the learning effects.

Nicolas Denoyelle et al. developed a platform (VirtualEnaction) for systemic neuroscience simulation[38]. VirtualEnaction can be used to validate functional models of the brain. Besides, some rehabilitation platform has been developed for performing sensorimotor tasks[39–43]. Scott L. Delp et al. developed an open-source software (OpenSim) to create and analyze dynamic simulations of Movement in rehabilitation science[43]. Marika Demers et al. proposed a 2D virtual environment for arm rehabilitation after stroke[41]. Zbytniewska Monika et al. design a robotic device for the assessment of hand sensorimotor impairments[42]. James V. McCall et al. proposed a platform for finger rehabilitation in children with hemiplegic cerebral palsy[40]. Niccolò Butti et al. develop a VR-based platform about social prediction improvement and rehabilitation intensive training for pediatric patients[39]. **Table 3** listed the comparisons between these platforms with the platform presented here.

For the future research directions, the platform is compatible with noninvasive neural recordings technique (EEG) to measure the neural response during sensorimotor control. Investigating the mapping relationship between sensorimotor control and the EEG spatial-frequency signal, we might reveal the brain mechanism of sensorimotor control. It will be an important research question for understanding the human sensorimotor system. Moreover, most of the theory in this study is based on optimal control after learning. The stopping time for training is quite arbitrarily and empirically chosen in the study. It is therefore an important issue to evaluate whether participants hit a hard asymptote or a plateau[44]. Future studies could investigate the sensorimotor learning study using WheelCon to further test the asymptote/plateau and their possible explanations with sensorimotor learning theory.

ACKNOWLEDGMENTS:

We thank Mr. Zhengyang Wang for reshaping the scripts, shooting and editing the video, and Mr. Ziyuan Ye for editing the video. This study got support from CIT Endowment & National Science Foundation (to JCD) and Boswell fellowship (to QL).

DISCLOSURES:

The authors disclose that they have no conflicts of interest.

REFERENCES:

1. Franklin, D.W., Wolpert, D.M. Computational Mechanisms of Sensorimotor Control. *Neuron*. **72** (3), 425–442 (2011).
2. Bays, P.M., Wolpert, D.M. Computational principles of sensorimotor control that minimize uncertainty and variability. *The Journal of Physiology*. **578** (2), 387–396 (2007).
3. Desmurget, M., Grafton, S. Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*. **4** (11), 423–431 (2000).
4. Sanger, T.D., Merzenich, M.M. Computational Model of the Role of Sensory Disorganization in Focal Task-Specific Dystonia. *Journal of Neurophysiology*. **84** (5), 2458–2464 (2000).
5. Mohler, H., Okada, T. Benzodiazepine receptor: demonstration in the central nervous system. *Science*. **198** (4319), 849–851 (1977).
6. Muller, L., Chavane, F., Reynolds, J., Sejnowski, T.J. Cortical travelling waves: mechanisms and computational principles. *Nature Reviews Neuroscience*. **19** (5), 255–268 (2018).
7. Zhang, H., Watrous, A.J., Patel, A., Jacobs, J. Theta and Alpha Oscillations Are Traveling Waves in the Human Neocortex. *Neuron*. **98** (6), 1269-1281.e4 (2018).
8. Blinks, J.R., Rüdel, R., Taylor, S.R. Calcium transients in isolated amphibian skeletal muscle fibres: detection with aequorin. *The Journal of Physiology*. **277** (1), 291–323 (1978).
9. Gallivan, J.P., Chapman, C.S., Wolpert, D.M., Flanagan, J.R. Decision-making in sensorimotor control. *Nature Reviews Neuroscience*. **19** (9), 519–534 (2018).
10. Sanger, T.D. Basic and Translational Neuroscience of Childhood-Onset Dystonia: A Control-Theory Perspective. *Annual Review of Neuroscience*. **41** (1), 41–59 (2018).
11. Todorov, E. Optimality principles in sensorimotor control. *Nature Neuroscience*. **7** (9), 907–915 (2004).
12. Todorov, E., Jordan, M.I. Optimal feedback control as a theory of motor coordination. *Nature Neuroscience*. **5** (11), 1226–1235 (2002).
13. Wolpert, D.M., Flanagan, J.R. Computations underlying sensorimotor learning. *Current Opinion in Neurobiology*. **37**, 7–11 (2016).
14. Kiper, P. et al. Computational models and motor learning paradigms: Could they provide insights for neuroplasticity after stroke? An overview. *Journal of the Neurological Sciences*. **369**, 141–148 (2016).
15. Cluff, T., Crevecoeur, F., Scott, S.H. Tradeoffs in optimal control capture patterns of human sensorimotor control and adaptation. *bioRxiv*. 730713 (2019).
16. Nakahira, Y., Liu, Q., Bernat, N., Sejnowski, T., Doyle, J. Theoretical foundations for layered architectures and speed-accuracy tradeoffs in sensorimotor control. *2019 American Control Conference (ACC)*. 809–814 (2019).

17. Körding, K.P., Wolpert, D.M. Bayesian integration in sensorimotor learning. *Nature*. **427** (6971), 244–247 (2004).
18. Chambers, C., Sokhey, T., Gaebler-Spira, D., Kording, K.P. The development of Bayesian integration in sensorimotor estimation. *Journal of Vision*. **18** (12), 8–8 (2018).
19. Karmali, F., Whitman, G.T., Lewis, R.F. Bayesian optimal adaptation explains age-related human sensorimotor changes. *Journal of Neurophysiology*. **119** (2), 509–520 (2017).
20. Gori, J., Rioul, O. Information-Theoretic Analysis of the Speed-Accuracy Tradeoff with Feedback. *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. 3452–3457 (2018).
21. Trendafilov, D., Polani, D. Information-theoretic Sensorimotor Foundations of Fitts' Law. *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–6, at <https://doi.org/10.1145/3290607.3313053> (2019).
22. Fitts, P.M., Peterson, J.R. Information capacity of discrete motor responses. *Journal of Experimental Psychology*. **67** (2), 103–112 (1964).
23. Fitts, P.M. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*. **47** (6), 381–391 (1954).
24. Nakahira, Y., Matni, N., Doyle, J.C. Hard limits on robust control over delayed and quantized communication channels with applications to sensorimotor control. *2015 54th IEEE Conference on Decision and Control (CDC)*. 7522–7529 (2015).
25. Nakahira, Y., Liu, Q., Sejnowski, T.J., Doyle, J.C. Fitts' Law for speed-accuracy trade-off describes a diversity-enabled sweet spot in sensorimotor control. *arXiv:1906.00905 [eess, q-bio]*. at <http://arxiv.org/abs/1906.00905> (2019).
26. Jafari, M. Neural Correlates of Sensorimotor Control in Human Cortex: State Estimates and Reference Frames. at <https://resolver.caltech.edu/CaltechTHESIS:05302019-163325527> (2019).
27. Miall, R.C., Wolpert, D.M. Forward Models for Physiological Motor Control. *Neural Networks*. **9** (8), 1265–1279 (1996).
28. Battaglia-Mayer, A., Caminiti, R., Lacquaniti, F., Zago, M. Multiple Levels of Representation of Reaching in the Parieto-frontal Network. *Cerebral Cortex*. **13** (10), 1009–1022 (2003).
29. Scott, S.H. Optimal feedback control and the neural basis of volitional motor control. *Nature Reviews Neuroscience*. **5** (7), 532–545 (2004).
30. Saunders, J.A., Knill, D.C. Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research*. **152** (3), 341–352 (2003).
31. Insperger, T., Milton, J., Stépán, G. Acceleration feedback improves balancing against reflex delay. *Journal of The Royal Society Interface*. **10** (79), 20120763 (2013).
32. Birbaumer, N. Breaking the silence: Brain–computer interfaces (BCI) for communication and motor control. *Psychophysiology*. **43** (6), 517–532 (2006).
33. Liu, Q., Farahibozorg, S., Porcaro, C., Wenderoth, N., Mantini, D. Detecting large-scale networks in the human brain using high-density electroencephalography. *Human Brain Mapping*. **38** (9), 4631–4643 (2017).
34. Nicolelis, M.A.L. Brain–machine interfaces to restore motor function and probe neural circuits. *Nature Reviews Neuroscience*. **4** (5), 417–422 (2003).
35. Nordin, A.D., Hairston, W.D., Ferris, D.P. Faster Gait Speeds Reduce Alpha and Beta EEG Spectral Power From Human Sensorimotor Cortex. *IEEE Transactions on Biomedical Engineering*.

67 (3), 842–853 (2020).
36. Hallett, M. Transcranial magnetic stimulation and the human brain. *Nature*. **406** (6792), 147–150 (2000).
37. Madhavan, S., Weber, K.A., Stinear, J.W. Non-invasive brain stimulation enhances fine motor control of the hemiparetic ankle: implications for rehabilitation. *Experimental Brain Research*. **209** (1), 9–17 (2011).
38. Denoyelle, N., Pouget, F., Viéville, T., Alexandre, F. VirtualEnaction: A Platform for Systemic Neuroscience Simulation (2014).
39. Butti, N. et al. Virtual Reality Social Prediction Improvement and Rehabilitation Intensive Training (VR-SPIRIT) for paediatric patients with congenital cerebellar diseases: study protocol of a randomised controlled trial. *Trials*. **21** (1), 82 (2020).
40. McCall, J.V., Ludovice, M.C., Blaylock, J.A., Kamper, D.G. A Platform for Rehabilitation of Finger Individuation in Children with Hemiplegic Cerebral Palsy. *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*. 343–348 (2019).
41. Demers, M., Levin, M.F. Kinematic Validity of Reaching in a 2D Virtual Environment for Arm Rehabilitation After Stroke. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. **28** (3), 679–686 (2020).
42. Zbytniewska, M. et al. Design and Characterization of a Robotic Device for the Assessment of Hand Proprioceptive, Motor, and Sensorimotor Impairments. *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*. 441–446 (2019).
43. Delp, S.L. et al. OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement. *IEEE Transactions on Biomedical Engineering*. **54** (11), 1940–1950 (2007).
44. Gray, W.D. Plateaus and Asymptotes: Spurious and Real Limits in Human Performance. *Current Directions in Psychological Science*. **26** (1), 59–67 (2017).

Figure 1

Click here to access/download;Figure;Figure1.tif

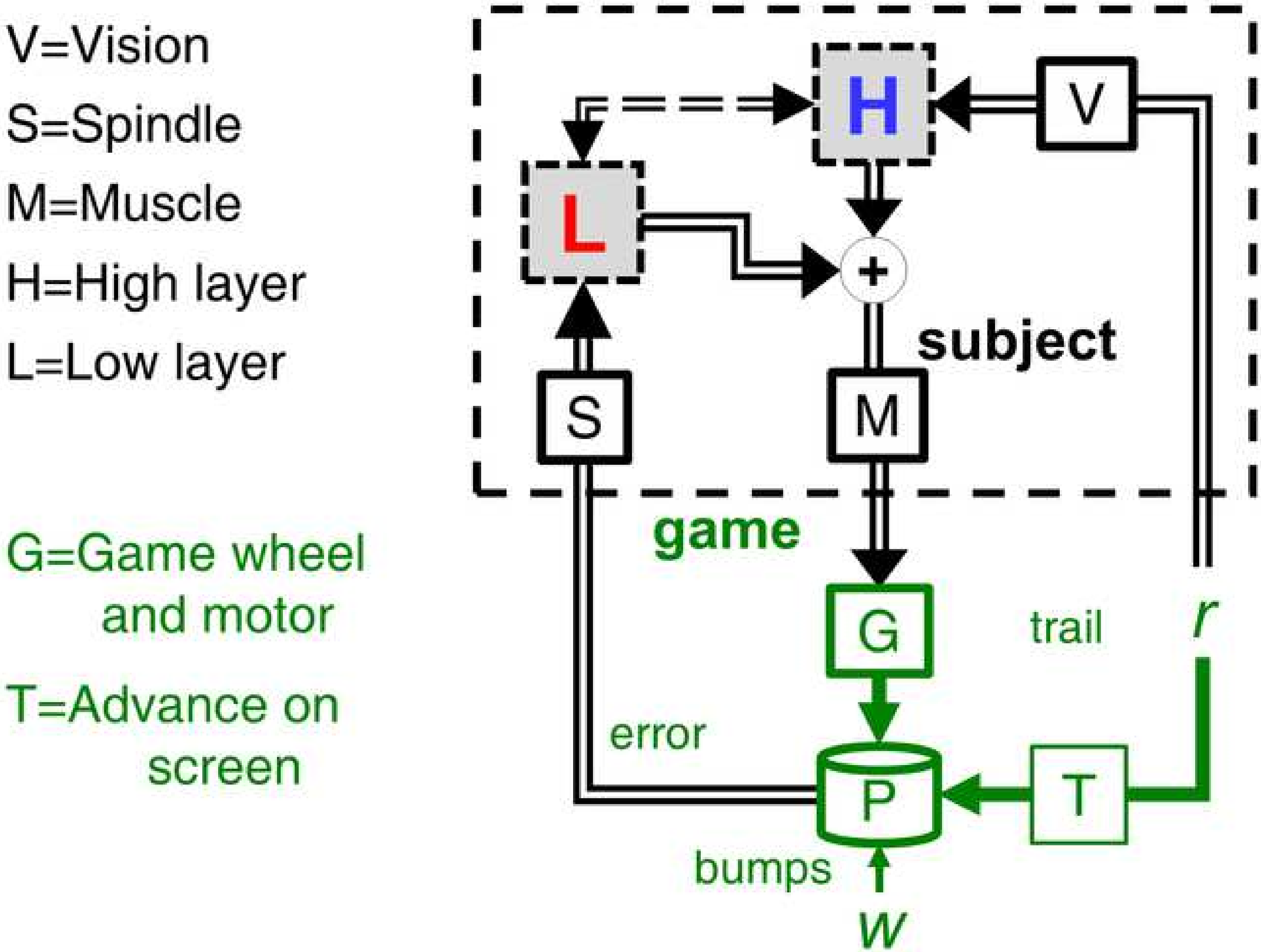

Figure 2

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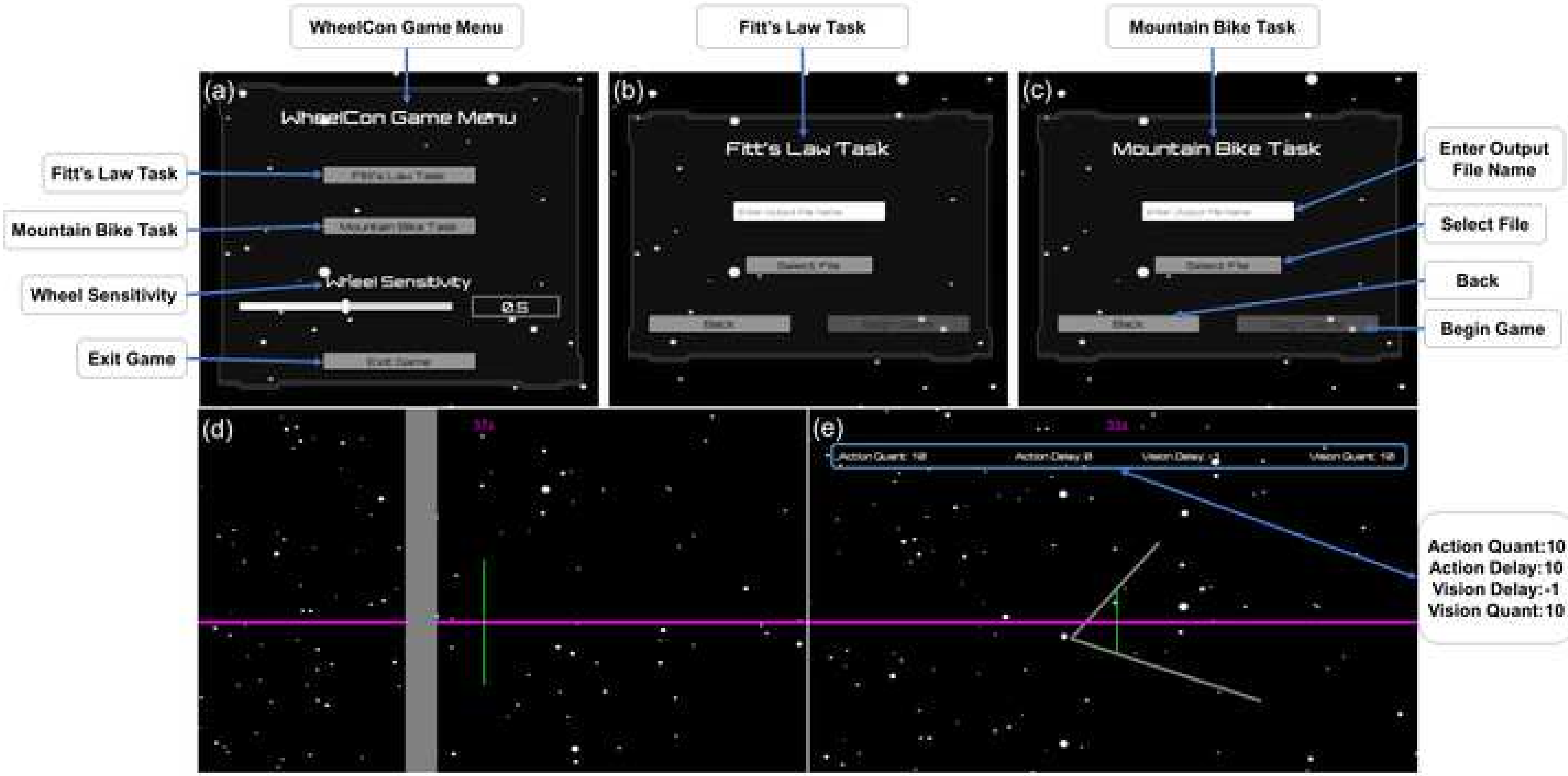

Figure 3

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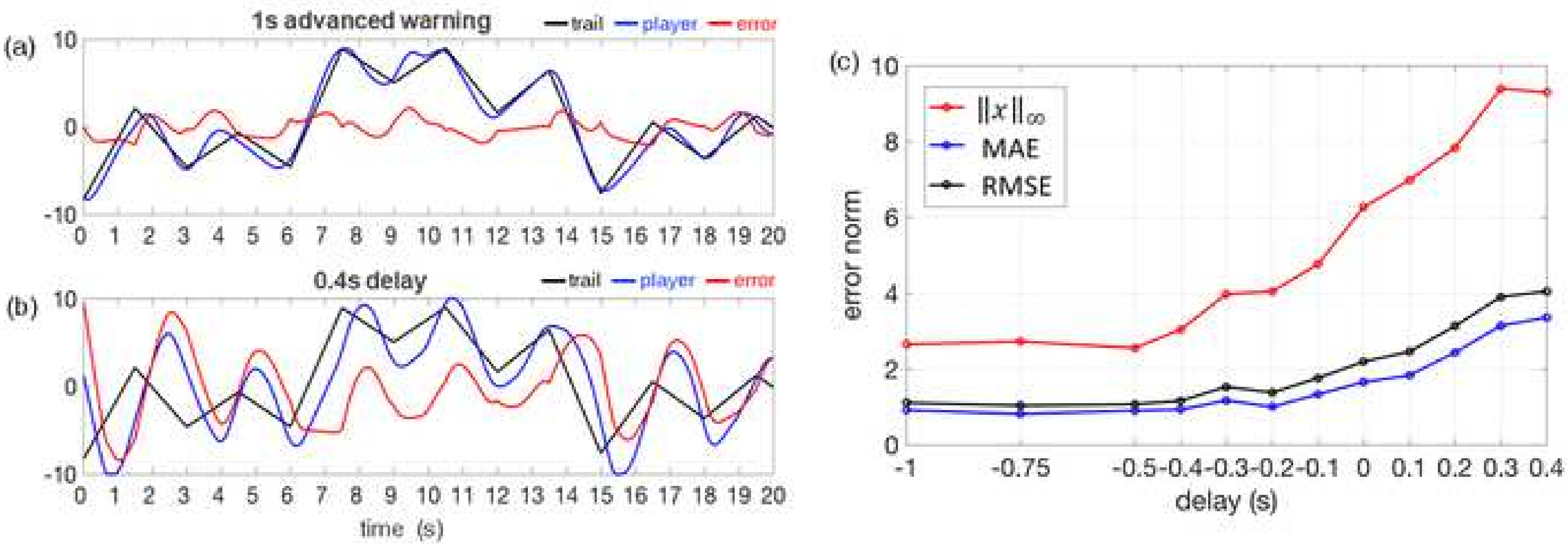

Figure 4

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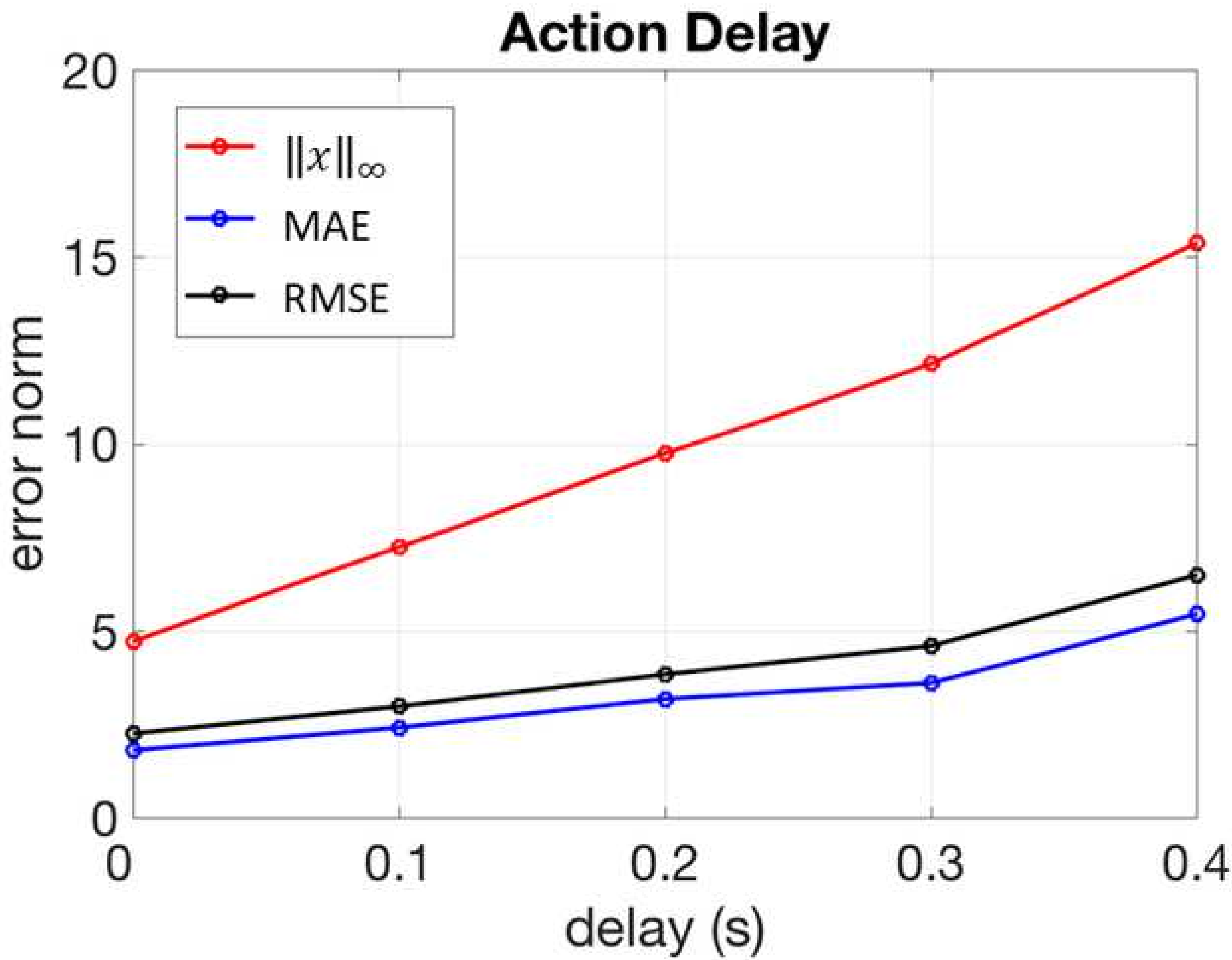

Figure 5

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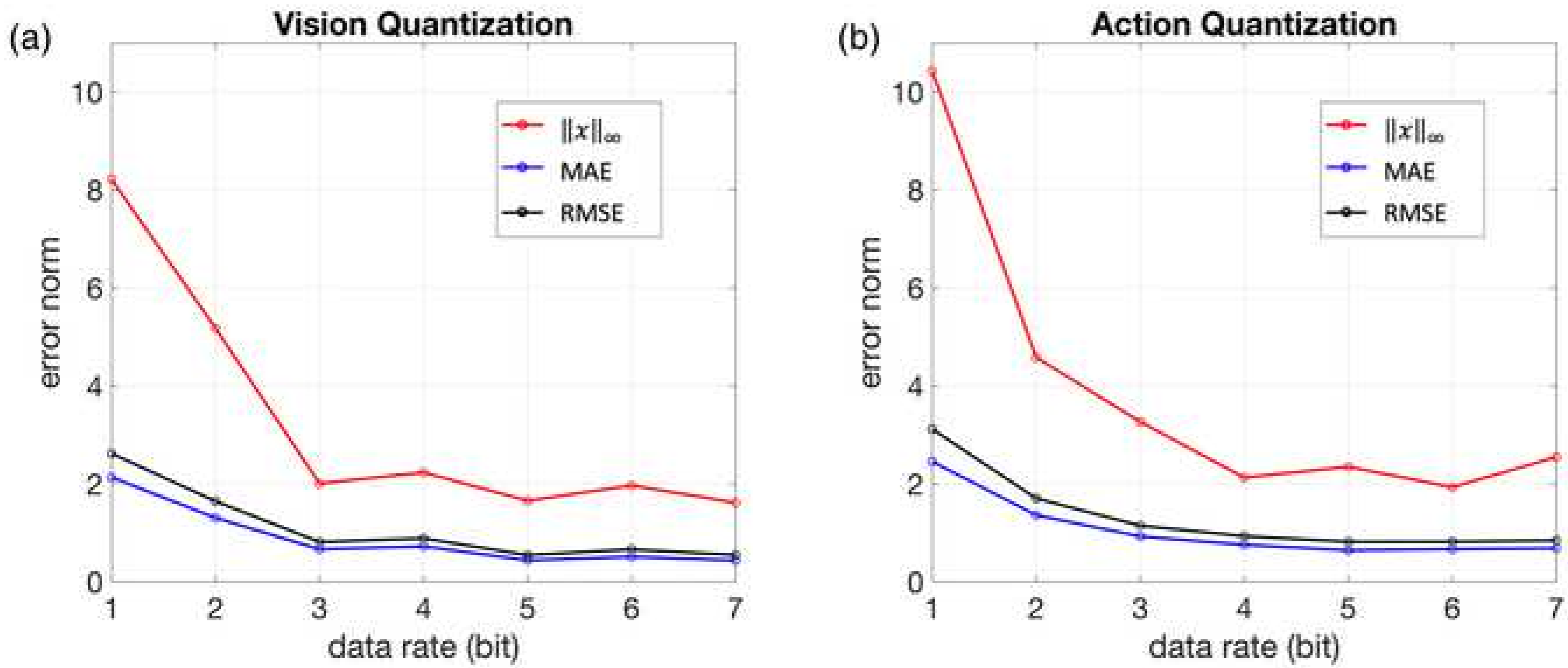

Figure 6

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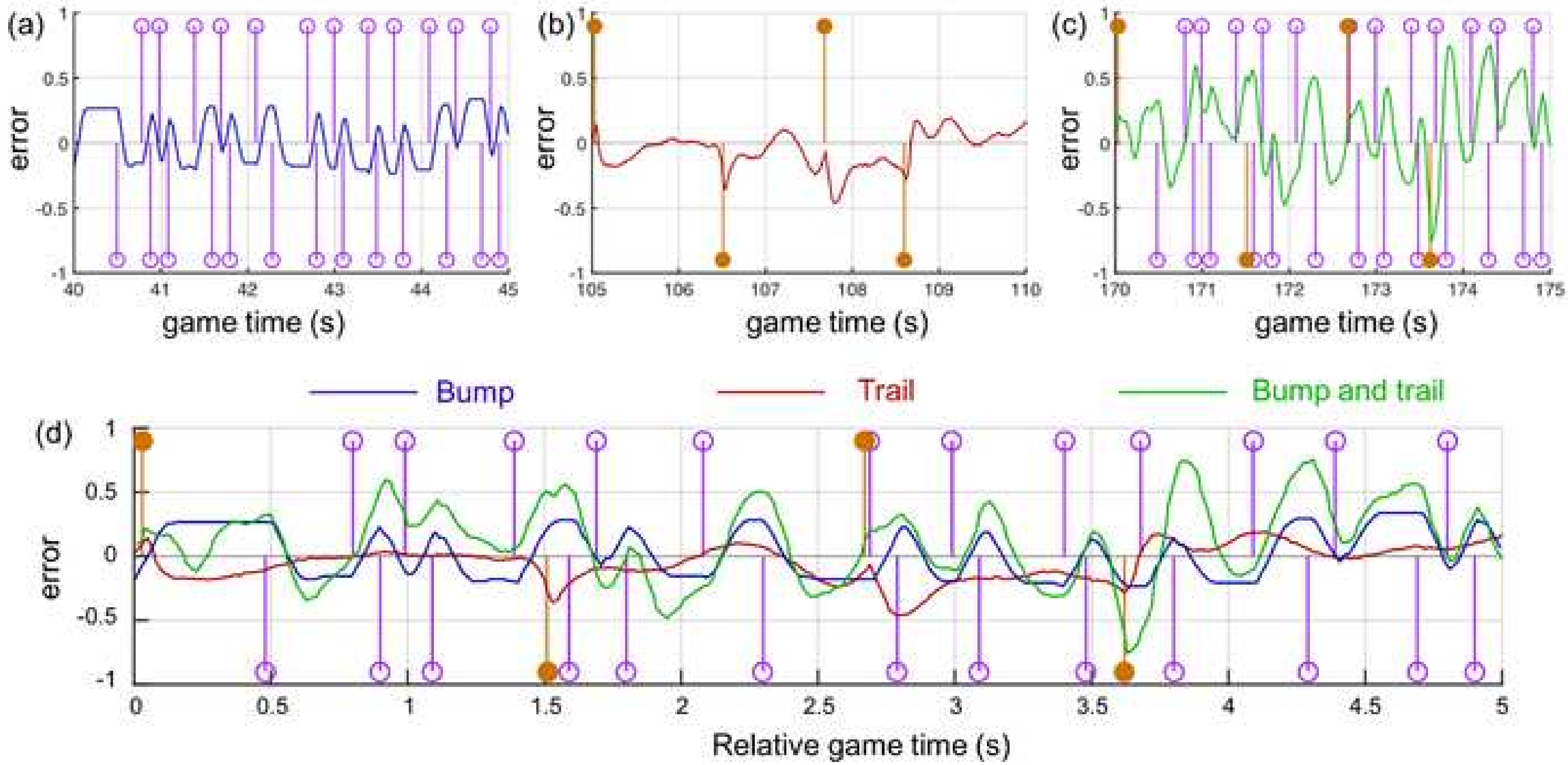

Table 1 Click here to access/download;Table;Table1.xlsx

notation	variable	unit	constrains
w(t)	Bump distu	n Newton	$0 \leq w(t) \leq 100$
r(t)	Trail disturl	100 pixels	$0 \leq r(t) \leq 100$; $r(t) \perp w(t)$
T_{vis}	Vision adva	second	$-1 \leq T_{vis} < 1$
T_{act}	Action dela	second	$0 \leq T_{vis} < \infty$
R_{vis}	External da	bit	$1 \leq R_{vis} \leq 10$
R_{act}	External da	bit	$1 \leq R_{act} \leq 10$
Q_{vis}	External qu	1	$Q_{vis} = 2^{R_{vis}}$
Q_{act}	External qu	1	$Q_{act} = 2^{R_{vis}}$

Table 2

Click here to access/download;Table;Table2.xlsx

notation	variable	unit
t	Time	second
x(t)	Error dynar	100 pixels
u(t)	Control pol	degree

Table 3

Click here to access/download;Table;Table3.xlsx

Platform	Open Source ?
2D Virtual Environment (2DVE)	No
ETH MIKE	No
OpenSim	Yes
PneuGlove	No
VirtualEnaction	Yes
VR-SPIRIT	No
WheelCon	Yes

Download Link

https://opensim.stanford.edu/

http://virtualenaction.gforge.inria.fr/

https://github.com/Doyle-Lab/WheelCon

Function

1.Reach-to-grasp movements for arm rehabilitation after stroke;

1.For the assessment of proprioceptive,motor and sensorimotor hand impairments

1. To study neuromuscular coordination; 2. Let users develop models of musculoskeletal structures and create dynamic simulations of movements.

1.To train and evaluate finger individuation in children with hemiplegic cerebral palsy

1. For systemic neuroscience simulation; 2. To verify the functional models of the brain; 3.To experiment complex survival behaviors

1.To improve predictive abilities in social scenarios. 2. Rehabilitation intensive training for paediatric patients

1. To verify the Fitts' Law in human sensorimotor control; 2.To study the layered architecture in Sensorimotor control.

 Click here to access/download;Table of Materials;JoVE_Table_of_Materials.xlsx

Name of Material/Equipment	Company	Catalog Number	Comments/Description
Gaming Wheel	Logitech		
Windows 10 OS	Microsoft		

Click here to access/download;Rebuttal Letter;Response to Reviewers.docx

Dear editor,

We have revised the manuscript based on the comments. The changes in the manuscript have highlighted in red. Here is the point-to-point response (highlighted in blue) to the reviewers' comments.

Reviewer #1:
The manuscript titled: "WheelCon: A wheel control-based gaming platform for studying human sensorimotor Control" proposes an interesting concept and it seems to me that it has already been revised once however, yet, this manuscript cannot be recommended for online publication as I am not satisfied with the work proposed/written and would like this work to be revised. If the authors do not agree with the comments made or there are any suggestions authors have not considered, I welcome authors details justification. In this case, please authors need to resubmit a revised version by describing all changes made and explaining how authors have followed the referee (me) suggestions.

We would like to thank the Reviewer for the constructive comments on the manuscript. We have done our best to improve the manuscript, by addressing the points raised. We hope the revised manuscript would satisfy the Reviewer and be accepted as a publication. Please see the point-to-point response in the following response letter. The corresponding changes in the manuscript have been highlighted.

1) Some of the labels given to x/y axis in the graphs are not properly readable/visible. Please make them more visible and clear. Also, write them using the same font as some of the labels have been edited using editing software later after experiments. Please put the original graphs obtained from the experiments with original labels and do not alter them later on using any editing software. This is what I have sensed after observing the graphs deeply.

We thank the Reviewer for pointing out this issue. We have regenerated the graphs from the experiments with original x and y labels and made them readable. Figure 5 (a) and (b) have been modified with the same range of y axis. We hope we address this issue well in the revised graphs.

2) The size (width & height) of some of the graphs are also not the same. Some graphs are a bit smaller and some are larger. I request the authors to please make them uniform and consistent.

We have regenerated the graphs in a uniform and consistent form. We hope we address this issue well in the revised graphs.

3) I could not find any figure number. Please give numbering to all of the graphs particularly mentioned at the end after the text in the manuscript.

In our revised manuscript, we have cited each figure and table in the manuscript, and we have numbered all the graphs and tables mentioned in the section “FIGURE AND TABLE LEGENDS” at the end of the text in the manuscript.

4) The legends (labels inside graphs) are not visible in most of the graphs. Besides,

the text in the game snapshots mentioned in the manuscript (from (a) to (e)) are also not properly visible and unclear. Can the authors tell me what text has been written inside the text boxes in these game snapshots? Besides textboxes what have been written on the buttons inside these game snapshots.

We thank the Reviewer for pointing out this point. We have regenerated the graphs and make the legends more visible. Besides, we also regenerated the game snapshots and pointed out each textboxes and buttons in a more visible manner. We hope we address this issue well in the revised graphs.

5) The size and contribution of the manuscript are short and look at the number of authors (9) I would suggest reducing the number of authors to at least 5 or 6 to make it more authentic, original and publishable online. (This comment is a polite request. I beg a pardon If it hurts any author).

We understand the Reviewer's concern on the number of authors. Although the length of the manuscript is short, the code for the platform was developped and tested by a group of people. We also have proposed a feedback model to explain the observed behavioral results from the motor experiments.

Among the authors, JC Doyle conceptualize the research idea; Q Liu, A Mohideen, SH Choi, A Pan and DM Ho developped the software; Y Nakahira and Z Liang developped the feedback model; Q Liu, A Mohideen, A Dai performed the motor experiments; Q Liu and Z Liang wrote the manuscript.

It is very hard to not recognize someone's contribution as a coauthor. We hope the reviewer understands our will to maintain the authorlist.

6) Has the journal template/format for the manuscripts been followed or not? As the spaces between lines and paragraphs are not uniform and consistent.

We thank the Reviewer for pointing out the format issue. We have re-edited the manuscript following the journal’s template. Particularly, we have formatted the table in excel, as the request of the journal. We hope we address this issue well in the revised manuscript.

7) For the revised version (JoVE61092R1) I could not find any cover letter along with the point-by-point feedback or response.

We apologize for the mistake. We had a cover letter in the initial submission, and forgot to upload an updated version for the revised version. We have added the cover letter for the resubmission this time.

8) Some of the references (papers) have been wrongly cited in the text as the paragraphs/lines deliver something else and if one then goes to those cited articles for reading it conveys something else. Please cite only relevant references.

We thank the Reviewer for pointing out this point. We have checked each reference to make them approporiately cited.

9) For twelve pages' manuscript authors need to cite at least 30 to 35 articles such as strong citations from IEEE Transactions. Besides, please most of the citations should refer to respectable journals. In this manuscript, most of the citations are very old. Please cite at least 6 more relevant and recent articles (published in the last five years) to make them at least 30. I hope here authors can understand what I mean?

We thank the Reviewer's suggestion. We have enriched the citations and added around 15 recent citations in the revised manuscript.

10) Is there any other article published in 2020-2019 in which similar or related work is proposed? Could authors please explain the related improvements and proposed research work achieved particularly in 2020-2019 in not more than 10 lines?

We thank the Reviewer's suggestion. We have added a paragraph in the disucssion to compare our platform with the recent publications. Also, we have added a table (Table 3) which reviewed some other existing platforms and their functions.

11) It is Poorly formatted and composed manuscript, in some parts of the manuscript a single is enclosed in a single section/subsection such as 3.1,3.2, 3.3,3.4 etc. etc. The authors don't need to get discouraged, they should believe in themselves. Please improve the composition and presentation of the text and material in the manuscript it will increase the chances of the manuscript to be get accepted. Also, Authors need to improve spelling, grammatical and particularly semantic issues.

We thank the Reviewer for the suggestion. We have improved the composition and presentation of the text and materials in the manuscript. Also, we have checked the manuscript thoroughly, and largely improved the writing style of the manuscript. We hope the updated manuscript will satisfy the Reviewer.

12) Can you please cite the experimental studies on neuroscience by other authors using the same platform i.e. WheelCon?

Yes, we have cited two neuroscience citations [1,2] which used our WheelCon platform. Unfortunately, both works were conducted by our group. The platform was launched in github in 2019; however, no one except us knew the function of WheelCon. This is one of the main reasons why we would like to publish in JoVE with a video to show how to use WheelCon platform for sensorimotor studies.

[1] Yorie Nakahira, Quanying Liu, Natalie Bernat, Terry Sejnowski, John Doyle (2019). Theoretical foundations for layered architectures and speed-accuracy tradeoffs in sensorimotor control, American Control Conference (ACC), pp:809-814

[2] Yorie Nakahira, Quanying Liu, Terrence J Sejnowski, John C Doyle (2019). Fitts' law for speed-accuracy trade-off is a diversity sweet spot in sensorimotor control, arXiv preprint arXiv:1906.00905

13) Authors have straight away implemented Fitts' law. Please spend some time on explaining Fitt's law briefly.

We thank the Reviewer's suggestion. We have added a description for Fitt's Law in (line 74), and two relevant citations.

14) There are too many written "NOTES" in this manuscript. I would request the authors to reduce these NOTES by explaining it in any other acceptable way or layout.

We have reduced some "NOTES" and explaining it in an acceptable way. We hope the updated manuscript will satisfy the Reviewer.

15) Besides WheelCon, please authors are requested to explain the environment, tools, and supportive platforms on which the experiments are performed such as software's, hardware, libraries, packages, programming languages, etc. etc.

As suggested by the Reviewer, we have changed the description of the environment, tools, and supportive platforms in the subsection of System Preparation and Setup in the section of PROTOCOL. The text in the revised manuscript is as following.

"1.1. The basic hardware requirements are recommended with a 2GHz dual-core processor and 4GB system memory.

1.2. The gaming platform is built under the Unity platform, while programing language is C#. The Logitech gaming wheel driver and Logitech Steering Wheel SDK are needed for gaming platform development.

1.3. The gaming platform executable files only support Windows 10 Operating System (OS). Therefore, on a PC running Windows 10, download and install the corresponding racing wheel driver, then download the compressed WheelCon software (https://github.com/Doyle-Lab/WheelCon/archive/master.zip) and extract the files to the local hard drive. "

16) Please, can the authors compare their findings/results with existing state-of-the-art achievements/works in the form of a table?

We thank the Reviewer for the suggestion. This paper is drafted in a way to highlight the functions of platform, rather than the experimental findings in neuroscience. Therefore, we have added a table which surveyed some exisiting sensorimotor platforms.

17) I would like to know how the authors have validated and verified their experiments/ Model?

We thank the Reviewer for the suggestion. We have published/preprinted several papers under this platform to verify human sensorimotor control model.

Two works using WheelCon to verify the sensorimotor control model:
[1] Yorie Nakahira, Quanying Liu, Natalie Bernat, Terry Sejnowski, John Doyle (2019). Theoretical foundations for layered architectures and speed-accuracy tradeoffs

in sensorimotor control, American Control Conference (ACC), pp:809-814
[2] Yorie Nakahira, Quanying Liu, Terrence J Sejnowski, John C Doyle (2019). Fitts' law for speed-accuracy trade-off is a diversity sweet spot in sensorimotor control, arXiv preprint arXiv:1906.00905

A conference paper for an initial version of the platform:
[2] Quanying Liu, Yorie Nakahira, Ahkeel Mohideen, Adam Dai, Sunghoon Choi, Angelina Pan, Dimitar M Ho, John C Doyle (2019). Experimental and educational platforms for studying architecture and tradeoffs in human sensorimotor control, American Control Conference (ACC), pp:483-488

18) Please, authors, are requested to observe the platforms that have been used by other authors in their papers mentioned in the references section of this manuscript.

To the best of our knowledge, the platform has not been used by other groups in their papers. We hope the publication of this manuscript will boost the visibility of the platform and I will be glad to see WheelCon been widely used.

Reviewer #2:
Manuscript Summary:
This manuscript reports the development of a game-like app that allows to testing of aspects of human sensorimotor control, including the effects of visual and motor delays. The idea behind the development of this game is well-developed, and should be of general interest to researchers and educators in the field of human sensorimotor control, and potentially also game developers. I am not qualified to evaluate the code and technical (programming) aspects of the report, but the game/app appears to work as intended.

We thank the reviewer's comments.

Major Concerns:
1) My most major concern is that the report fails to identify that the "mountain biking task" is a combination of a pursuit and compensatory tracking task. These types of tasks are classic components of research on human sensorimotor performance, especially in terms of studying feedback loops, as the authors have described in the Introduction. I think that the use of these terms (pursuit tracking and compensatory tracking) should be necessary so that researchers will be able to recognize the function of the game.

We thank the Reviewer for pointing out this drawback. We have added a sentence in the introduction (**line 76**) to identify that the 'mountain biking task' is a combination of a pursuit and compensatory tracking task, which are two classic components of research on human sensorimotor performance, especially in terms of studying feedback loops.

2)Second, not very much information is provided about the Fitts' law task that is included in the app. Does the experimenter have the ability to control variables such as the width of the targets and the distance between them? I understand that the data output includes information about error, but typically also in a Fitts' law task, researchers would want to record the movement durations of the individual pointing movements and it is not clear that the data output provides this capacity.

We thank the Reviewer for this question. The Fitts' law tasks have two roles in this paper. First, indeed, the width of the targets and the distance can be designed in the input files of app. Additional implanted delays to human vision (monitor) and action (wheel) can be manipulated in the input file as well. In this way, WheelCon platform can be applied to study the effects of delay and disturbances in feedback control loops [1]. Second, Fitts' law task can be used as a benchmark task to verify the recordings from platform. So we kept Fitt's law task in the platform for the other groups may use it to calibrate the platform.

[1] Yorie Nakahira, Quanying Liu, Terrence J Sejnowski, John C Doyle (2019). Fitts' law for speed-accuracy trade-off is a diversity sweet spot in sensorimotor control, arXiv preprint arXiv:1906.00905

Minor Concerns:

2) I have some minor concerns over the graphs. Typically it would be recommended that when graphs are presented side by side, that the y-axes would be scaled uniformly- for example, the graphs comparing tracking error as a function of visual delays and action delays. I understand that the authors do not intend to draw conclusions about the different effects of the two types of delay, thus this is only a minor point. A little more concerning is the x-axis of the action delay. My understand of the methods used by the app is that action delays are implemented at 0s, .15s, .30s, .45s, .60s, and .75s but the values on the x axis correspond to 0s, 0.1, 0.2, 0.3, and 0.4s.

We thank the Reviewer for pointing out this mistake. We have double checked the source data, and we confirm the action delay is correct in the figure. We have modified the increments by 0.1s and reaches to 0.4s.

We have replaced the sentence as ' Adjusting T_{act} every 30 seconds, T_{act} starts at 0 s, and increments by 0.1 s until it reaches 0.4 s.' (Line 361).

Reviewer #3:

Manuscript Summary:

The authors present WheelCon - a platform to design "video games" that provides the ability to customize a simulation of a particular visuo-motor control task - riding a mountain bike (note that while the authors use the term video game, many would probably refer to it as a "gamified" task environment instead). The platform allows a host of parameters of importance to the study of visuo-motor control to be manipulated independently (noting that it's probably not the case that all parts of that combined space create viable environments - i.e., some combinations of parameters will undoubtedly be "unplayable"). These dimensions include delay in control/feedback, presence of noise, and multiple feedback loops.

We would like to thank the Reviewer for the constructive summary of the manuscript.

Major Concerns:
N/A

Minor Concerns:
Overall the rationale, design, and methods appear solid and are clearly presented, so I have no major concerns. I have just a few comments regarding parts of the discussion that don't appear to obviously align with the presented protocol.

1) Line 452: The authors indicate that the "most critical step in this protocol is to train, but not over train the participant in advance." If this is indeed the "most critical step" it seems as if it would need quite a bit more exposition to explicitly explain what that means (quantitatively speaking in terms of the measures that are available).

We thank the Reviewer for the concern about the statement of "most critical step". Actually, WheelCon platform can also be used to study the learning effects with the naive participants who did not train in the game. However, our feedback control model is built to explain the robust control performance in human sensorimotor system, rather than the learning effects or the tiredness of motor control. Therefore, we used "most critical step in this protocol is to train, but not over train the participant in advance." This protocol is corresponding to the model.

To solve the ambiguity of "most critical step", we have replaced the sentence as 'In this protocol it is important to train, but not over train, the participant in advance, otherwise the learning effects or the tiredness of participants will impact the predictions of our model.' (Line 452).

2) Line 464: The authors indicate that "Matching these parameters across groups is necessary." This also needs more exposition. If the point is to train subjects to a certain point, why couldn't every group be trained with the same wheel sensitivity, etc. until they reach a certain threshold? For example, older populations might just need longer training than younger populations. And more generally in terms of theory, if these parameters are different between groups, how would one know that the sensorimotor process for the task is still the same across groups? (i.e., if the parameters are different depending on group, how would one know if any differences in behavior reflect group differences or parameter differences?).

We thank the Reviewer for the question about the group comparison. We agree with you that it is hard to compare between groups without matching these parameters across groups.

It is easy to set the sensitivity parameter in our current study, for we only recuit young and healthy participants and their sensorimotor control is quite flexible.
Our concern is that the participants in some groups might not reach a stable, convergent performance when we fixed the parameter to an inappropriate value. For instance, the old participants might fail in training no matter how long they have

trained, for the system is too sensitive and the reaction time in old group is too slow. In this case, we would suggest the user to choose a low sensitivity for both the old and young group in order to compare the results.

We have added some expositions after the sentence "Matching these parameters across groups is necessary." to clarify it. We have added the following sentences in line 478.

" Here, we suggest the user to choose an appropriate sensitivity for both the old and young group in order to make a comparison."

3) Line 469: The authors indicate that they, "…only analyzed the data after the subjects were well trained and their performance became stable to avoid the learning effects." First, is there reason to expect that participants hit a hard asymptote rather than a plateau (e.g., see https://journals.sagepub.com/doi/abs/10.1177/0963721416672904)? Or reason to suspect that they're even in a flat spot (whether it's a plateau or asymptote) versus just in a slow phase of learning? How does this comment interact with the first comment above? It seems as if participants have stopped learning (as would be indicated by the statement that their performance is "stable"), then they're over trained (i.e., in many theories of learning that's the only point at which you'd hit a hard asymptote).

We thank the Reviewer for the question about the training problem. It is indeed an important issue to evaluae whether participants hit a hard asymptote or a plateau. Most of the thoery in this study is based on optimal control after learning. The stopping time for training is quite arbituarily and empirically chosen in our study. This is a limitation.

I would highly recommend a sensorimotor learning study using WheelCon to test the asymptote/plateau and their possible explanations with sensorimotor learning thoery, as a future direction. Thus, we add a sentence in discussion to point it out as a limitation and future direction with the suggested paper as a citation (line 499).