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MULTI-GAIN CONTROL: BALANCING DEMANDS FOR SPEED AND PRECISION

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Woodworth's Two-Component model (1899) partitioned speeded limb movements into two distinct phases: (1) a central ballistic open-loop mechanism and (2) a closed-loop feedback component. The present study investigated the implementation of multi-gain control configurations that utilized separate gain values optimized for each movement phase. A target acquisition task using Fitts' Law (1954) was performed within a virtual environment using multiple control devices with three gain settings: (1) mono-gain, (2) dual-gain, and (3) continuous gain. It was found that dual-gain and continuous gain configurations yielded lower movement times and information-processing rates than the mono-gain configurations. The secondary gain values presented in the dual-gain and continuous gain configurations were reported to mitigate oscillations around smaller targets that were responsible for additive settling time. Therefore, implementation of multi-gain control logic could help improve performance when navigating through large spaces and acquiring small targets.

Woodworth (1899) pioneered early research in manual control by examining speed, accuracy, and movement characteristics in continuous voluntary movements (Flach & Jagacinski, 2003). He was able to measure spatial accuracy, consistency of movements, and spatiotemporal characteristics of trajectories using a reciprocal pointing task (Elliot, Chua, & Helsen, 2001). Utilizing these metrics, he observed that for initial aiming attempts, the first portion of the limb movement was generally a rapid and uniform approach to the target. However, as distance to the target decreased, movement became slow, broke off into small sporadic adjustments in position, and finally stabilized on the target.

From these observations, Woodworth hypothesized a two-component model of goal-directed aiming where the control of speeded limb movements consisted of two distinct phases: (1) a central open-loop mechanism followed by (2) a closed-loop feedback-based component (Elliot, Chua, & Helsen, 2001). In Phase 1, an initial ballistic response maneuvers the limb into the vicinity of the target area. Once in the region, the limb comes under feedback-based control (Phase 2) where visual information regarding limb and target position is used to make adjustments in movement trajectories (Elliot, Chua, & Helsen, 2001).

For two-component based control systems, the standard has been to pick a gain that compromises between speed and precision (Kantowitz & Sorkin, 1983). In the present study, by examining each component—open-loop and closed-loop—we can independently optimize their gains based on stability constraints. A high gain is appropriate for the open-loop ballistic phase as it will get to the target vicinity faster. A lower gain is needed for the closed-loop mechanism to emphasize precision and make fine adjustments. Independent gain values for each movement phase should afford a more accurate, time efficient control system.

Preliminary testing supported this notion. In a condition using an Xbox controller with a single gain value (mono-gain), it was found that the value was set too high for the secondary closed-loop control phase. Participants could not get the cursor to stop oscillating and settle in on the smaller targets. They lacked the necessary precision to complete the task in a timely manner. Movement phases could no longer be efficiently controlled separately. However, once a dual-gain configuration was implemented, vast improvements in performance were observed as well as diminished oscillations. Thus, we found a way of getting around this compromise between speed and precision. Instead of having a single "optimal" gain, we introduced two different gain values for each movement phase that could be used at the discretion of the user.

The purpose of this experiment was to expand on preliminary findings in terms of multi-gain control. The performance of three continuous movement devices, each with three gain configurations, was examined. The three gain configurations used were (1) mono-gain, (2) dual gain, and (3) continuous gain. It was hypothesized that the multi-gain configurations (dual and continuous) would yield better performance than the mono-gain configuration. The transference of multi-gain control logic to each device was also examined. Subjects used each device with every gain configuration to complete a series of target acquisition tasks.

Method

Participants

Five participants (aged 23-36) working for Wright Patterson Air Force Base in Dayton, Ohio were used as participants. The participants were from the Human Effectiveness Directorate and worked in joint partnership with Wright State University on this project. Participants were not compensated and willingly participated.

Apparatus

Three devices were used: an Xbox 360 controller, Samsung Slate Tablet, and THRUSTMASTER Hotas Warthog Joystick and Throttle. The gain values available to participants ranged from 10 to 40 based on their configuration. The initial gain value for every device was set at 40. The mono-gain configuration was fixed at the initial gain. For the dual gain configuration, only the initial and lowest gain values were available and could be toggled back and forth using the device mechanisms. For the continuous gain configuration, the whole range of values (10-40) were available and could be scanned as a function of controller displacement (i.e., slowly depressing or releasing the Xbox trigger).

For the Xbox controller, the left thumbstick maneuvered the cursor around the screen. The left trigger served as the gain adjustor. Depressing the trigger gave access to the secondary gains. The Samsung Slate tablet had a first-order control scheme. A center crosshair was implemented at the intersection of four quadrants on the tablet display. Participants were required to drag their finger outward in any direction from the crosshair in order to move the cursor position. The three gain configurations were set up as follows: (1) Mono-gain—fixed at 40; (2) dual-gain—a button on the tablet display initiated the lower gain (10) when pressed and held; (3) continuous gain—a sliding scale adjusted values within the set parameters (10-40).

For the joystick and throttle, one hand was used to manipulate gain values on the throttle while the other hand was used to maneuver the cursor via the joystick.. For the dual gain, pushing the throttle to the most forward position initiated the lower gain while the opposite executed the highest gain. For the continuous gain, as the throttle was pushed forward, gain lowered as a function of displacement. And conversely, as the throttle was brought back, gain increased.

Procedure

The study took place inside a virtual environment. The environment was completely immersive with six walls and overhead projection panels. For this study, only 180 degrees of the environment was used. A gridded virtual landscape was displayed in front of the participant. Cursor position was indicated by a red dot. An equivalent number of targets of different widths and distances were systematically scattered around the space at varying angles of azimuth and elevation. Targets appeared at random within the environment.

Participants were seated in front of the virtual display. The control mappings and gain configurations for the device at hand were explained. After being briefed about the device, participants were given instructional steps related to the task: (1) visually search and locate the target; (2) activate the stationary home button at the bottom of the display using the cursor; (3) immediately drag the cursor onto the target to acquire; (4) repeat.

Design

Ten practice acquisitions were administered in order to get the participants accommodated to the task, device, and gain configuration; 300 recorded trials followed. Participants ran through nine conditions (3 devices x 3 gain configurations) twice for a total of 18 sessions. Each session took place at intervals of at least fifteen minutes to several days apart. Movement times (ms) were measured as the time from home button activation until target selection. Min, max, and mean movement times for each session were recorded for further analysis.

Fitts' Law was used to model human performance and compute information-processing rates. The angle of displacement from the home button to the target served as a measure of amplitude. Width was a measure of visual angle produced by each target. Information-processing rates (ms/bit) were computed for each block by plotting indexes of difficulty as a function of movement time for each trial. Gain manipulation histories were also recorded.

Results

Four 3 x 3 x 2 within-subjects repeated measures ANOVA's were conducted. The first factor was device, the second was gain configuration, and the third was block. An ANOVA was done for each of the following: (1) mean mimimum times, (2) mean maximum times, (3) mean movement times, and (4) mean information-processing rates. Mean values were calculated across participants by factor.

For minimum movement times, there were no significant main effects for device, gain configuration, or block. For maximum movement times, there were significant main effects for gain configuration (*F*(1.014, 4.057) = 10.373, $P < .05$) and block (*F*(1, 4) = 33.099, $P < .05$). The mono-gain configuration yielded the highest maximum movement times ($M = 15920.328$). The dual-gain yielded the second highest ($M = 7426.042$), and the continuous gain yielded the lowest ($M = 6712.310$). Block 2 ($M = 9104.156$) yielded better performance than Block 1 ($M = 10934.964$). There was a significant interaction between device and gain configuration (*F*(4, 16) = 3.526, $P < .05$).

For mean movement times, there were significant main effects for device (*F*(2, 8) = 25.953, $P < .05$) and gain configuration (*F*(1.062, 2.247) = 13.197, $P < .05$). The Xbox controller ($M = 2726.232$) and joystick ($M = 2965.792$) yielded significantly lower mean movement times than the tablet ($M = 3661.478$). For gain configuration, dual-gain ($M = 3003.938$) was significantly better than the mono-gain ($M = 3504.531$). Continuous gain ($M = 2845.033$) was significantly better than both. *Figure 1* shows average minimum, mean, and max movement times across participants for each block, gain configuration, and device.

For information-processing rates, there were significant main effects for gain configuration (*F*(1.039, 4.156) = 9.042, $P < .05$) and block (*F*(1, 4) = 28.238, $P < .05$). There was also a significant interaction between device and gain configuration (*F*(1.625, 6.498) = 4.498, $P < .05$). The dual-gain configuration ($M = 412.473$) yielded lower rates than the mono-gain configuration ($M = 565.792$). The continuous gain configuration ($M = 367.985$) yielded the lowest rates. Block 2 ($M = 431.540$) yielded significantly better performance than Block 1 ($M = 465.960$). *Figure 2* depicts mean information-processing rates across participants for each factor.

Discussion

Findings supported our hypotheses. Multi-gain configurations yielded lower mean and max movement times as well as lower information-processing rates. The continuous gain configuration performed the best. The dual-gain configuration performed second best and the mono-gain configuration performed the worst. Because of the sharp decrease in maximum movement times observed in the multi-gain configurations, we persist in that large max times in the mono-gain conditions were a result of excessive oscillation around the smaller targets. This problem was mitigated by the dual and continuous gain implementation. Secondary lower gain values added a level of precision in the closed-loop component that diminished oscillations and reduced maximum movement times. This reduction also led to lower mean movement times.

Further analysis of how participants used the dual and continuous gain configurations is needed to differentiate control strategies. Participants could have used a bang-bang control strategy in both cases, thus negating the perceived advantage of the continuous configuration. One limitation of our study was that the design was not completely counterbalanced due to time limitations and previously existing data. Thus, some of the variance in performance could be due to practice effects.

The transference of multi-gain control logic across devices was variable. In the Xbox and joystick conditions, we saw sharp improvements in performance going from mono-gain to dual-gain which did not appear in the tablet. In debriefing the subjects, we found that they were utilizing a different control strategy for the tablet. A "tapping" strategy was used to make small adjustments once in the vicinity of the target. That is, the participant would tap their finger on the display in order to move the cursor in small increments. This method of input allowed them to be more precise when acquiring smaller targets and negated the multi-gain configurations, likely explaining the observed interactions between device and configuration.

In conclusion, multi-gain configurations catering to the movement phases initially described by Woodworth yielded faster, more accurate performance than standard mono-gain setups. However, this multi-gain control logic seems to be limited by device characteristics such as method of input. Further analysis on gain manipulation histories is needed to reveal differences in control strategies.

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Tables and Figures

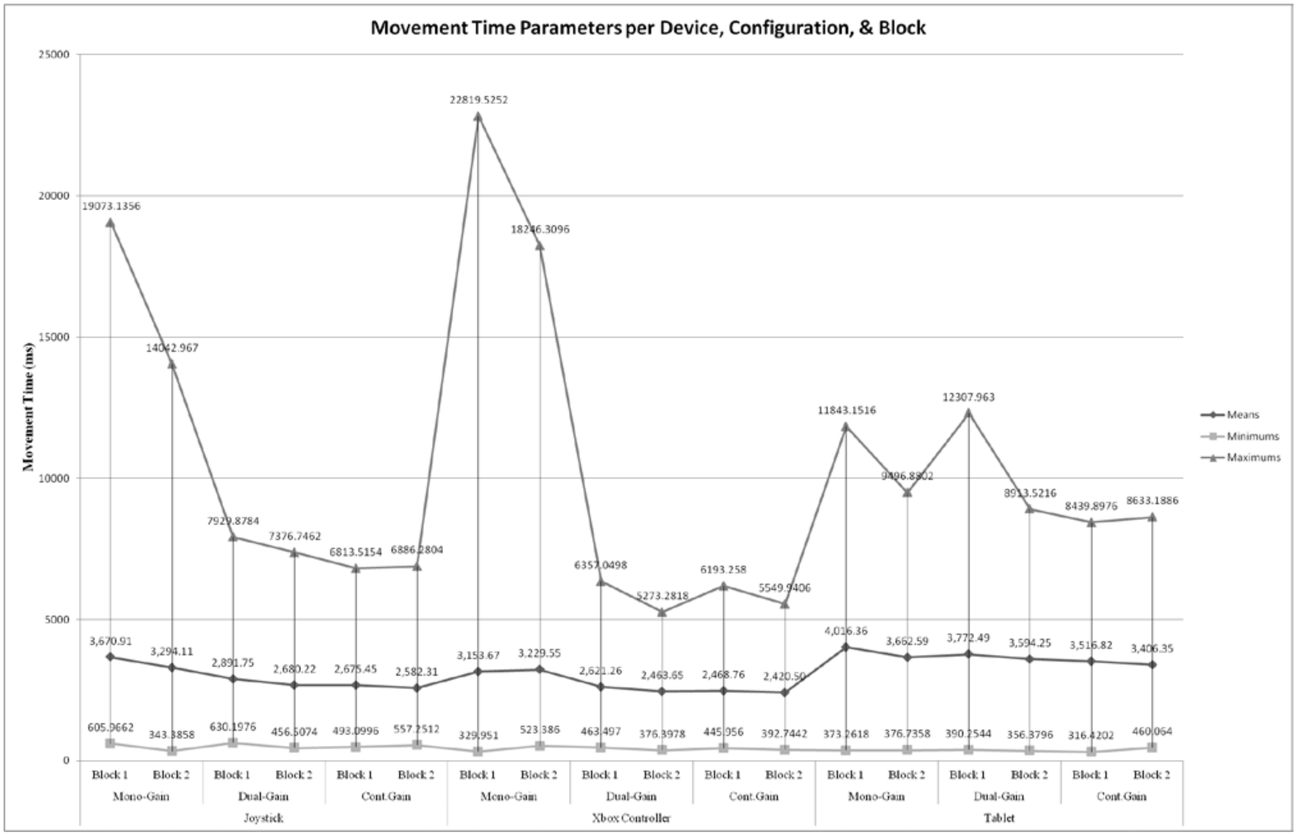

Figure 1. Mean movement time parameters (ms) across participants for device, configuration, and block.

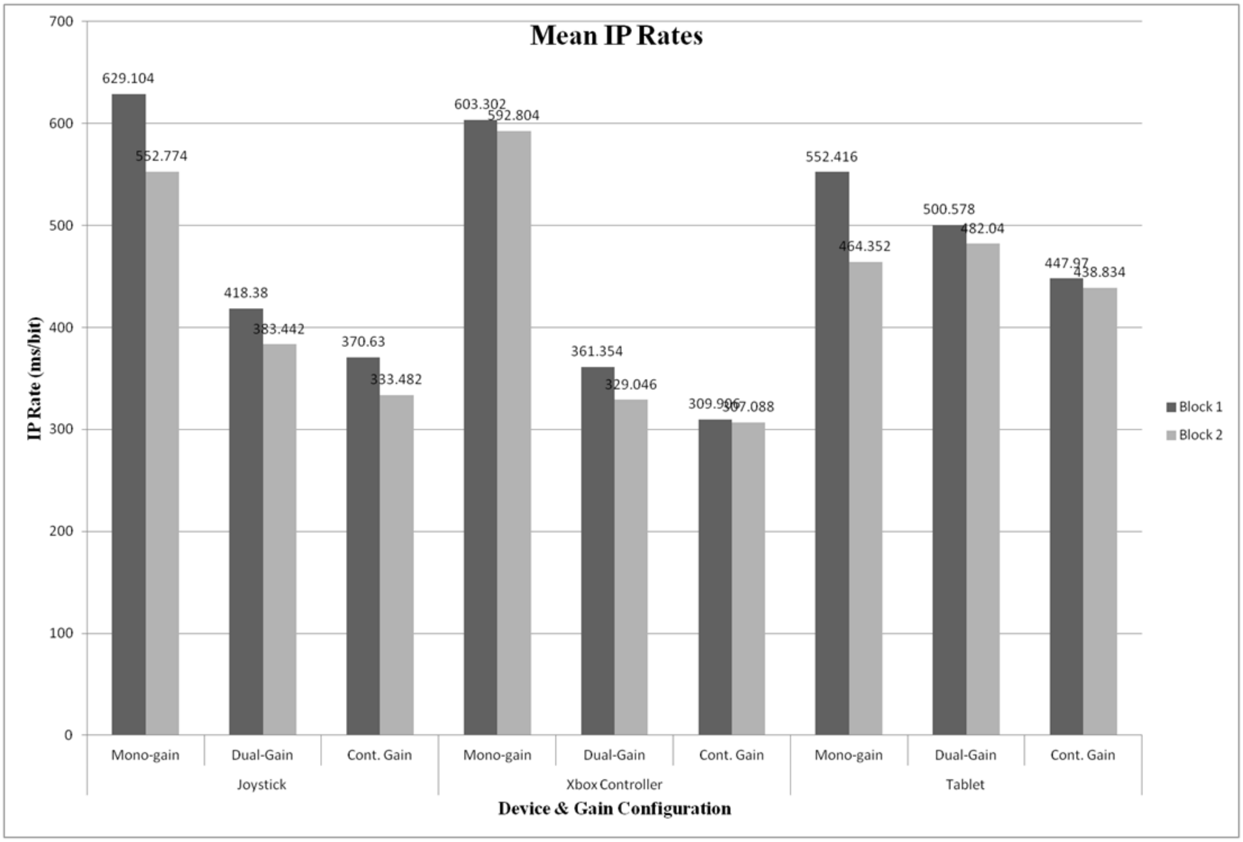

Figure 2. Mean information-processing rates (ms/bit) across participants for device, configuration, and block.

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