Training transfer and self-motion

THE EFFECTIVENESS OF SIMULATOR MOTION IN THE TRANSFER OF PERFORMANCE ON A TRACKING TASK IS INFLUENCED BY VISION AND MOTION DISTURBANCE CUES

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Abstract

The importance of physical motion in simulators for pilot training is strongly debated. The present experiment isolated different types of motion, a potentially important variable contributing to the controversy. Participants used a joystick to perform a target tracking task in a motion simulator built using a MOOG Stewart platform. Five training conditions compared training without motion (as one would train in a stationary simulator), with correlated motion, with disturbance motion, with disturbance motion isolated to the visual display, and with both correlated and disturbance motion. The test condition involved the full motion model with both correlated and disturbance motion. We analyzed speed and accuracy across training and test as well as strategic differences in joystick control. We found that training with disturbance provided better transfer to test conditions that included disturbance motion for accuracy, but not speed, and that training with disturbance motion produced different joystick control strategies compared to training without disturbance.

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INTRODUCTION

The use of flight simulators has become an increasingly common aspect of pilot training over the last few decades because it minimizes the risk of human injury and vehicular loss during training. Self-motion cues provided by expensive motion platforms are often key components of these simulated environments, but the effectiveness of full-body motion during these training sessions is still controversial (Bürki-Cohen, Sparko, & Bellman, 2011; Caro, 1979; McCauley, 2006; Valverde, 1973). Here, we use a motion simulator controlled by a MOOG Stewart platform to directly examine a potentially important variable that might provide some explanation for these discrepant findings: the presence of disturbance (e.g. turbulence) motion during training.

It is well documented that pilots prefer simulated environments that incorporate physical motion compared to those that do not (Bürki-Cohen et al., 2001; Hall, 1978; Ryan, Scott, and Browning, 1978; Woodruff, Smith, Fuller, & Weyer, 1976), but empirical evidence to support that motion simulators are superior is mixed. Some studies have shown that self-motion is a critical component during training (Lee & Bussolari, 1989; McDaniel, Scott, & Browning, 1983; Van der Pal, 1999), whereas other studies have found self-motion to be less important (Bürki-Cohen et al., 2001; Go, Bürki-Cohen, and Soja, 2000; Jacobs & Roscoe, 1975; Koonce, 1979; Woodruff et al., 1976). A number of meta-analyses have been conducted in an attempt to gain a clearer understanding of these inconsistent findings. Pfeiffer and Horey (1987) focused on 45 studies that examined the benefits of motion during simulator training on flight performance, and concluded in favour of training with motion. However, this meta-analysis included studies that did not directly manipulate self-motion, in addition to those that compared motion vs. no motion. Subsequent meta-analyses that have only included studies that use self-motion as an independent variable have not concluded in favour of training with motion. For example, a meta-analysis by Jacobs et al. (1990) found no significant improvement when comparing training conditions with vs. without self-motion. Similarly, Vaden and Hall (2005) found a small advantage for training with self-motion compared to no self-motion, but they cautioned about making any firm conclusions because of specific limitations to their study. It is difficult to make strong conclusions from these two meta-analyses because they examined a relatively small number of studies. More importantly, they did not take into account the different types of motion that can be used during training.

Pilots can experience two distinct types of motion when flying an aircraft: Correlated/maneuvering motion and uncorrelated/disturbance motion. Correlated motion is that which occurs as a direct result of the pilot's steering (i.e., the motion is correlated to the actions of the pilot). In contrast, disturbance motion refers specifically to motion that is not correlated with the pilot's actions. These disturbances include all motions associated with the environment that occur independently of the pilot's controls, including turbulence (e.g., low-frequency disturbances from weather), vibration (e.g., high-frequency disturbances from motor vibrations), and vehicular damage (e.g., unexpected engine failure or loss). The distinction between studies that include or do not include disturbance motion is critical, as it may explain some of the discrepant findings in the transfer-of-training literature. Indeed, in a recent comprehensive meta-analysis, de Winter et al. (2012) found a significant effect in favour of training with motion amongst the 24 studies included in the analyses, but this benefit was largely contingent on studies that included disturbance motion. This suggests that the efficacy of training with motion depends on the presence of disturbance motion during training; however, this has yet to be tested directly.

In the present study, we directly examine the disturbance motion hypothesis by training participants on a target tracking task in a motion simulator built using a MOOG Stewart platform. There were five training conditions designed to compare training without motion (as one would train in a stationary simulator), with correlated motion, with disturbance motion, and with both correlated and disturbance motion. The fifth training condition isolated the effect of disturbance forces on the visual display from the effect of disturbance forces on motion of the platform (platform motion was turned off). From the perspective of the participant, the only evidence of the disturbance was visual. This is a less complex implementation of disturbance in the sense that it does not require simulator motion, but as far as we are aware, this has yet to be examined in these types of training studies. This condition is important because if disturbance motion during training improves transfer-of-training effects, we can then ask whether physical motion is necessary, or whether visual disturbance alone may provide equal benefits.

Following training, participants in all five conditions were tested on the visual tracking task under the full simulation that included both correlated motion and disturbance motion. We evaluated performance by looking at measures of speed and accuracy on the target tracking task, as well as measures of joystick control that may shed light on the strategic control of performance.

METHODS

Participants

We recruited 79 students (42 males) from McMaster University as volunteers or in exchange for course credit. Data from 4 participants were excluded due to hardware errors; the remaining 75 individuals were distributed across 5 conditions (15 participants per condition). Participants had normal or corrected to normal vision. The procedures for this experiment fulfilled the requirements of the Canadian tri-council policy on ethics and were approved by the McMaster Ethics Research Board.

Simulator

The simulator pod is supported by a MOOG © platform with six-degrees-of-freedom motion (Moog series 6DOF2000E). All stimuli were controlled by a program coded in C++ using the Vega Prime (Presagis) library. The program was hard real-time loop synchronized to a 60Hz signal. Target stimuli were presented on a 42” (diagonal) LCD panel with a resolution of 1920 x 1080 pixels and refresh rate of 60 Hz. Participants sat in an automobile style bucket seat bolted to the floor at centre of mass inside the simulator pod; this position maintained an approximate distance of 120 cm between eyes and the LCD display screen. Participant responses were recorded with a USB connected Logitech joystick ©. The joystick was mounted on a t-shaped apparatus that allowed for comfortable use on the lap. White audio noise was played inside the simulator to mask the sound of the motors. Output from two cameras mounted inside the simulator pod (one facing the screen and one facing the participant) was monitored by the experimenter to ensure that problems did not occur during data collection.

Visual stimuli

A simple virtual environment was created by presenting white clouds and blue sky across the full 1920 x 1080 pixel display for the duration of each trial. The display screen emulated the window of the vehicle through which the participant viewed sky and clouds as well as a target location superimposed upon the sky and clouds (Figure 1). The target tracking task required participants to use a joystick to move the vehicle left or right so the centre of the display screen was centred at the target location. To aid targeting, a crosshair was fixed at the centre of the screen for the duration of the trial; the crosshair was a white fixation cross at the centre of a red square (5.6 cm x 5.6 cm, subtending a visual angle of 2.67°). The target location was indicated by a blue circle (diameter 5.6 cm, visual angle 2.67°) presented along the horizontal meridian of the screen (i.e. sky) in a random location between 9.3 cm (4.4°) and 23.2 cm (10.9°) from centre of crosshair to centre of target circle (Figure 1).

Motion system

The motion system is a second order model with one degree of freedom that uses a combination of linear filters to simulate the movement of a mass with damping driven by forces (Figure 2). The inputs are forces generated by joystick movements or by noise injected into the model. The output is the change in position or orientation of the vehicle, calculated by integrating the forces acting on it.

Joystick input

Joystick movements made by participants were added to our motion system in order to calculate both the position of the crosshair and motion platform. Crosshair movement included inertial forces typically associated with joystick use. Therefore the movement of the joystick directed the crosshair rather than indicate its exact location. From the perspective of the participant, moving the joystick would appear to pull the crosshair in the direction of their joystick movement.

Motion stimuli

Vibration noise refers to medium-frequency noise motion (1 – 5 Hz) that was added to our force model in order to mimic engine and vehicle vibration typically experienced when operating a motor vehicle. Movement generated by these vibrations was not meant to move the participant's crosshair off target. Vibration noise was added to our model whenever the simulator platform was active. In addition to audio white noise, vibration noises helped to dampen the sound generated by the movement of the simulator platform.

Correlated motion refers to the movement of the simulator pod in response to movements of the joystick by the participant. In the present experiment we are working with lateral left and right movements only; the participant moves the joystick to shift the central crosshair to the location of the target circle. The displacement of the joystick is translated to movement of the simulator pod which accelerates laterally to the left (or right) to a maximum displacement of 20 cm from the centre starting position. From the perspective of the participant within the virtual environment, moving the joystick to the left or right moves the vehicle to the left or right, respectively.

Disturbance motion refers to low-frequency turbulence that mimics random wind forces. The turbulence is injected into the model as random left and right lateral forces at 20% of the maximum force produced by joystick movements, with random duration (less than 1.5 s). This disturbance motion is added to the model in addition to vibration noise (1 – 5 Hz) that mimics engine and vehicle vibration. A sine wave with a phase of 3 s modelled the wind bursts. The phase of wind bursts was modulated so that it was possible for the participant to experience more than one wind burst during a trial (approximately 2 per trial). From the perspective of the participant within the virtual environment, these forces are experienced as random wind bursts that blow the vehicle slightly off target.

Training Conditions

There were 5 training conditions, within which we manipulated the type of simulated motion experienced by the participant. In each of the 5 conditions, the model of the motion system is the same (Figure 2). What differed was whether disturbances were injected into the model, and whether output was translated into a physical change in position of the vehicle. In other words, the physical motion could be turned on or off, and this could be done independently for the correlated motion and the disturbance motion (Figure 2). Moreover, in each of the 5 conditions, the participant was able to see the position of the vehicle represented as changes in the visual display in response to correlated motion (i.e., left and right joystick movements produced left and right movements of the visual stimuli across the display), and in response to disturbance motion in conditions in which disturbances were injected into the model. The 5 training conditions can be described as follows (Table 1 summarizes the type of motion experienced by the participant in each condition; Figure 2 illustrates control in the motion model to achieve these conditions).

VT: In the *visual tracking task only* training condition (VT), both the physical correlated motion and the physical disturbance motion were turned off. The simulator remained in its parked position throughout these training blocks. Visually, the participant was able to see changes in the position of the vehicle represented as changes in the visual display in response to correlated motion (i.e., left and right movements in response to joystick movements), but not in response to disturbance motion (i.e., the left and right movements due to disturbance caused by random wind bursts was turned off).

VT-CM: In the *visual tracking task with correlated simulator motion* condition (VT-CM), the correlated motion was turned on and the physical disturbance motion was turned off. The vehicle moved left and right in response to joystick movements. Visually, the participant was also able to see changes in the position of the vehicle represented as changes in the visual display in response to correlated motion (i.e., left and right movements in response to joystick movements), but not in response to disturbance motion (i.e., the left and right movements due to disturbance caused by random wind bursts was turned off).

VT-CMDM: In the *visual tracking task with correlated simulator motion and disturbance motion* condition (VT-CMDM), all of the physical motion was turned on. The vehicle moved left and right in response to joystick movements, and also moved left and right in response to the disturbance forces. Visually, the participant was able to see changes in the position of the vehicle due to both correlated and disturbance motion (i.e., left and right movements in response to joystick movements as well as the random left and right movements due to disturbance caused by random wind bursts). Note that this training condition represents the complete simulation, and is identical to the test condition.

VT-DM: In the *visual tracking task with disturbance motion but no correlated motion* condition (VT-DM), the physical correlated motion was turned off and the physical disturbance motion was turned on. The vehicle moved left and right in response to the disturbance forces, but did not physically move in response to joystick movements. Visually, the participant was able to see changes in the position of the vehicle due to both correlated and disturbance motion (i.e., left and right movements in response to joystick movements as well as the left and right movements due to disturbance caused by random wind bursts).

VT-visD: In the *visual tracking task with visual disturbance but no simulator motion* condition (VT-visD) the physical correlated motion was turned off. Disturbance forces were injected into the model, but physical motions were turned off. The simulator remained in its parked position throughout these training blocks. Visually, the participant was able to see changes in the position of the vehicle due to both correlated and disturbance motion (i.e., left and right movements in response to joystick movements as well as the left and right movements due to disturbance caused by random wind bursts).

Table 1: The 5 training conditions summarized with respect to type of motion.

Training Condition	Visual correlated motion	Physical correlated motion	Visual disturbance motion	Physical disturbance motion
VT	✓			
VT-CM	✓	✓		
VT-CMDM	✓	✓	✓	✓
VT-DM	✓		✓	✓
VT-visD	✓		✓	

Procedure

The experiment session was approximately one hour in duration for each participant. Participants were randomly assigned to one of the 5 training conditions described above (VT, VT-CM, VT-CMDM, VT-DM, or VT-visD). There were two training blocks (200 trials per block) followed by two test blocks (200 trials per block). The trials in the test blocks were identical to the trials in the VT-CMDM training blocks. Short breaks were provided between blocks; the participant was able to exit the simulator pod during breaks if desired. In the figures and analyses, the training blocks are referred to as practice blocks P1 and P2, and the test blocks are referred to as test blocks T1 and T2.

Each trial began with the background of sky and clouds; superimposed on the background was the crosshair (white cross inside a red square) at the center of the screen and a blue target circle at a random location along the horizontal midline to the left or right of centre. The task was to track the target as quickly and as accurately as possible by using the joystick to move the crosshair to the position of the blue target circle, so that the edges of the square fully contained the circle (Figure 1). From the perspective of the participant within the virtual environment, moving the crosshair was equivalent to moving the vehicle. Trials were 3 s in duration. At the end of each trial the display was replaced by a grey screen for 334 ms, followed immediately by the onset of the next trial.

Dependent variables

Performance was evaluated based on several measures. *Accuracy* reflects the proportion of trials successfully tracked. A target was considered successfully tracked if the center of the crosshair remained within 10% of the center of the target circle for at least 500 ms. *Track time* is evaluated for successfully tracked targets only, and reflects the elapsed time from the onset of the trial to the onset of the window within which the target is successfully tracked.

We also evaluated performance based on joystick movements, including measures of *error integral*, and joystick control in terms of *movement* and directional *switches*. Figure 3 illustrates 5 trial examples (2 successfully tracked; 3 not successfully tracked) showing relative positions of the target circle, crosshair, and joystick over the duration of the trial. The crosshair represents changes in the position of the vehicle in response to joystick movements during the trial and is reset to centre position at the beginning of the next trial. To compute the error integral on each trial, the distances are normalized (to account for different target positions) and the error is calculated as area under the curve that defines the deviation of the centre of the crosshair from the centre of the target position.

Joystick control was evaluated in two ways. One measure examined the extent of joystick movement in terms of the difference between the current position compared to the centre neutral position; data points were recorded at 60 Hz, measured as a proportion of maximum joystick range, and integrated over the 3 second trial duration. The resulting measure for each trial was normalized to account for different target positions. Smaller measures of joystick movement are associated with more efficient joystick control. The second measure of joystick control examined directional corrections or switches, executed to correct a movement in the wrong direction, or as a strategy to slow or stop vehicle movement, or as a result of overshooting the target. In noisy environments with disturbance motion it may be more difficult to move the crosshair directly to the target without overshooting. When the crosshair overshoots the target location it is necessary to bring it back with a joystick movement in the opposite direction. We counted the number of joystick direction switches defined as crossing the centre (neutral position) of the stick.

RESULTS

Each measure (accuracy, tracking time, joystick error integral, joystick movement, and joystick switches) was statistically examined by performing a mixed-model ANOVA crossing the 5 factor between-subject variable Training Condition (VT, VT-CM, VT-CMDM, VT-DM, VT-visD) with the 4 factor within-subject variable Block (P1, P2, T1, T2). Paired-sample t-tests examined practice effects within each of the training conditions.

Presentation of the results is organized according to whether the training conditions involved disturbance motion or not. The two *No Disturbance* conditions are VT (visual tracking only) and VT-CM (with correlated motion); neither involved disturbance motion during the first 2 blocks (P1 and P2). The three *Disturbance* conditions are VT-CMDM (with correlated and disturbance motion), VT-DM (with disturbance motion), and VT-visD (with visual disturbance but no physical motion); each included random disturbance motion of some kind during the first 2 blocks (P1 and P2). Recall that the final test blocks (T1 and T2) were identical to VT-CMDM, which represents the full motion model (Figure 2).

Accuracy

Accuracy improved across blocks, $F(3,70) = 30.88$, $p < 0.01$, $\eta^2 = 0.31$. A significant interaction between block and training condition, $F(12,70) = 2.50$, $p = 0.04$, $\eta^2 = 0.13$, helped to interpret the non-significant main effect of training condition, $F(4,70) = 1.63$, $p = 1.76$. These effects were further examined by looking at pairwise comparisons (Figure 4).

No disturbance conditions: For both the VT and VT-CM training, respectively, accuracy improved during practice, from P1 to P2 (VT: $t(14) = 2.70$, $p = 0.02$; VT-CM: $t(14) = 4.79$, $p < 0.01$). However, accuracy declined in the test blocks, evidenced by reduced accuracy from P2 to T1 (VT: $t(14) = -2.90$, $p = 0.05$; VT-CM: $t(14) = -3.73$, $p < 0.01$), and from P2 to T2 (VT: $t(14) = -3.94$, $p < 0.01$; VT-CM: $t(14) = -3.40$, $p < 0.01$).

Disturbance conditions: For the 3 training conditions with disturbance motion, VT-CMDM, VT-DM, and VT-visD, respectively, accuracy improved during practice, from P1 to P2 (VT-CMDM: $t(14) = 3.52$, $p < 0.01$; VT-DM: $t(14) = 6.65$, $p < 0.01$; VT-visD: $t(14) = 3.60$, $p < 0.01$). In contrast to the no disturbance training, participants in the disturbance conditions did show a continued increase in accuracy from practice to test. This is supported by improved accuracy from P1 to T1, (VT-CMDM: $t(14) = 5.67$, $p < 0.01$; VT-DM: $t(14) = 4.05$, $p < 0.01$; VT-visD: $t(14) = 2.54$, $p < 0.01$), and from P1 to T2 (VT-CMDM: $t(14) = 3.42$, $p < 0.01$; VT-DM: $t(14) = 6.04$, $p < 0.01$; VT-visD: $t(14) = 2.57$, $p < 0.01$).

Thus, accuracy improved during practice for all conditions, and continued to improve at test for training conditions with disturbance motion; however accuracy decreased from practice to test for training conditions with no disturbance. It could be argued that this pattern of results supports a transfer-of-training effect only for training that includes disturbance motion.

Pairwise comparisons within each block revealed differences between training conditions with and without disturbance motion only during the practice blocks P1 and P2 (P1: VT > VT-CMDM, $t(28) = 2.25$, $p = 0.03$; VT > VT-visD, $t(28) = 2.04$, $p = 0.05$; VT-CM > VT-DM, $t(28) = 2.16$, $p = 0.04$; VT-CM > VT-visD, $t(28) = 2.60$, $p = 0.02$; P2: VT > VT-CMDM, $t(28) = 2.84$, $p = 0.01$; VT > VT-visD, $t(28) = 2.40$, $p = 0.02$; VT-CM > VT-CMDM, $t(28) = 2.22$, $p = 0.04$; VT-CM > VT-visD, $t(28) = 2.97$, $p = 0.01$). There were no significant differences between the 5 training conditions in either of the test blocks (T1 and T2). This pattern of results suggests a different slant on our hypothesis above – even though participants trained without disturbance motion show a decrease in accuracy (compared to P2) when they encounter disturbance motion at test (T1 and T2), their performance in T1 and T2 is just as good at the groups who train with disturbance motion. From that perspective, it makes no difference whether training incorporates disturbance motion or not. We will revisit this hypothesis when we look at measures of joystick control.

Target track time

Target track time was sensitive to practice; the time required to successfully track was reduced across blocks, $F(3,70) = 17.23$, $p < 0.01$, $\eta^2 = 0.20$. There was no effect of training condition, $F(3,70) = 0.46$, $p = 0.76$, and no interaction, $F(3,70) = 0.97$, $p = 0.50$. Thus, there was a general improvement with practice (Figure 5), but there was no evidence for differences between the training conditions in terms of transfer of training effects. We can say that in this task, any differences in benefit of training with motion, compared to no motion, is not a benefit in speed.

Error integral

The error integral is sensitive to target track time, because the faster the target is tracked, the smaller the measure of spatial deviation between the crosshair and the target circle, but the error integral also captures variance related to magnitude of joystick movements, and the extent to which the crosshair may overshoot the target position (see illustration in Figure 3). We observed a practice effect, in that the magnitude of the error was reduced across blocks, $F(3,70) = 11.59$, $p < 0.01$, $\eta^2 = 0.14$. However, the interaction between block and training condition $F(12,70) = 1.50$, $p = 0.14$, and the main effect of training condition did not reach significance $F(4,70) = 0.69$, $p = 0.60$.

Basically, we found that the error integral reflected the same pattern of practice effects as target tracking time, and there was no statistical evidence that differences in training conditions resulted in differences in training transfer (Figure 6).

Joystick control (extent of movement)

The extent of joystick movements is measured as deviation of the joystick from centre neutral position over the 3 second trial. This provides a performance measure that may index differences in strategy, as some conditions may encourage a greater number of movements and/or larger movements (Figure 7). The extent of movement increased across blocks, $F(3,70) = 75.70$, $p < 0.001$, $\eta^2 = 0.52$. Training condition was also significant, $F(4,70) = 15.44$, $p < 0.001$, $\eta^2 = 0.50$, and there was a significant interaction between block and training condition, $F(12,70) = 23.90$, $p < 0.001$, $\eta^2 = 0.60$.

No-disturbance conditions: For both the VT and VT-CM training conditions, extent of joystick movements became smaller with practice, from P1 to P2 (VT: $t(14) = -6.36$, $p < 0.01$; VT-CM: $t(14) = -6.18$, $p < 0.01$). However, the extent of joystick movement increased dramatically for the test blocks, which introduced disturbance motion. These increases were measured between P1 and T1 (VT: $t(14) = 12.80$, $p < 0.01$; VT-CM: $t(14) = 14.74$, $p < 0.01$), between P1 and T2 (VT: $t(14) = 10.04$, $p < 0.01$; VT-CM: $t(14) = 14.61$, $p < 0.01$), between P2 and T1 (VT: $t(14) = 29.17$, $p < 0.01$; VT-CM: $t(14) = 27.60$, $p < 0.01$), and between P2 and T2 (VT: $t(14) = 19.91$, $p < 0.01$; VT-CM: $t(14) = 23.56$, $p < 0.01$). *Disturbance conditions:* VT-CMDM and VT-visD extent of joystick movements became smaller with practice, from P1 to P2 (VT-CMDM: $t(14) = -3.41$, $p = 0.03$; VT-visD: $t(14) = -4.63$, $p < 0.01$). None of the other comparisons reached significance ($p > 0.05$).

Pairwise comparisons within each of the practice blocks (P1 and P2) suggested that the extent of joystick movements in the training conditions without disturbance motion (VT and VT-CM) was small compared to the extent of joystick movements in the training condition with disturbance motion (VT-CMDM, VT-DM, and VT-visD). This was the case for both P1 (VT vs. VT-CMDM: $t(28) = -7.44$, $p < 0.001$; VT-CM vs. VT-CMDM: $t(28) = -12.79$, $p < 0.001$; VT vs. VT-DM: $t(28) = -6.90$, $p < 0.001$; VT-CM vs VT-DM: $t(28) = -9.86$, $p < 0.001$; VT vs. VT-visD: $t(28) = -5.04$, $p < 0.001$; VT-CM vs. VT-visD: $t(28) = -6.67$, $p < 0.001$), and for P2 (VT vs. VT-CMDM: $t(28) = -7.62$, $p < 0.001$; VT-CM vs. VT-CMDM: $t(28) = -11.52$, $p < 0.001$; VT vs. VT-DM: $t(28) = -7.90$, $p < 0.001$; VT-CM vs VT-DM: $t(28) = -10.80$, $p < 0.001$; VT vs. VT-visD: $t(28) = -7.08$, $p < 0.001$; VT-CM vs. VT-visD: $t(28) = 9.97$, $p < 0.001$).

Importantly, training condition was a critical factor for interpreting performance during the test blocks. Participants who trained with correlated motion, but not disturbance motion, tended to have reduced joystick movements during the test blocks compared to the groups who trained with disturbance motion. This was maintained over T1 (VT-CM vs. VT-CMDM: $t(28) = -2.05$, $p = 0.012$; VT-CM vs. VT-DM: $t(28) = -3.33$, $p = 0.010$; VT-CM vs. VT-visD: $t(28) =$ -

2.75, $p = 0.005$) and over T2 (VT-CM vs. VT-CMDM: $t(28) = -1.92$, $p = 0.015$; VT-CM vs. VT-DM: $t(28) = -2.55$, $p = 0.006$; VT-CM vs. VT-visD: $t(28) = -2.55$, $p = 0.001$).

In summary, the groups that trained with no disturbance motion appeared to employ qualitatively different strategies from practice to test, in which they learned to reduce the extent of joystick movements during the training blocks, then expanded the extent of their movements during test when disturbance motion was introduced. In contrast, the groups that trained with disturbance motion learned to use larger movements during training, and this strategy did not change with practice nor between practice and test. Moreover, training without disturbance motion appeared to have a long-term effect on joystick movements, such that even after two blocks of practice with the full motion model (T1 and T2), the extent of joystick movements did not increase to the level of the groups who trained with disturbance motion.

Joystick control (direction switches)

Another measure of strategic joystick control is the number of direction switches (Figure 8). This may be a measure of compensatory (back and forth) corrections, or responses to a noisy environment. The number of direction switches increased across blocks, $F(3,70) = 86.54$, $p < 0.001$, $\eta^2 = 0.55$. There was also a significant effect of training condition, $F(4,70) = 40.48$, $p < 0.001$, $\eta^2 = 0.70$, and a significant interaction between block and training condition, $F(12,70) = 46.06$, $p < 0.001$, $\eta^2 = 0.73$.

No-disturbance conditions: The VT-CM training condition showed a decrease in the number of joystick direction switches during the practice blocks (P1 compared to P2: $t(14) = -3.13$, $p = 0.045$); all the training conditions showed this trend, suggesting that practice promotes more efficient responding and fewer direction switches. This differed between practice and test, depending on training condition. Both the VT and VT-CM training conditions produced a greater number of direction switches in the test blocks than in the practice blocks. This increase was observed from P1 to T1 (VT: $t(14) = 12.34$, $p < 0.01$; VT-CM: $t(14) = 8.68$, $p < 0.01$), from P1 to T2 (VT: $t(14) = 13.40$, $p < 0.01$; VT-CM: $t(14) = 8.60$, $p < 0.01$), from P2 to T1 (VT: $t(14) = 13.11$, $p < 0.01$; VT-CM: $t(14) = 8.76$, $p < 0.01$), and from P2 to T2 (VT: $t(14) = 13.52$, $p < 0.01$; VT-CM: $t(14) = 8.50$, $p < 0.01$).

Disturbance conditions: The VT-CMDM, VT-DM, and VT-visD conditions all showed a trend toward reduction in numbers of joystick direction switches across practice sessions (P1 compared to P2), but this was significant only for VT-CMDM ($t(14) = -2.07$, $p = 0.049$) and VT-visD ($t(14) = -3.73$, $p = 0.01$). None of the other comparisons were significant ($p > 0.05$).

Pairwise comparisons examining differences between training conditions within each block illustrated the difference between disturbance and no disturbance training. The VT and VT-CM groups made fewer direction switches in P1 compared to VT-CMDM ($t(28) = -13.84$, $p < 0.001$; $t(28) = -15.95$, $p < 0.001$), VT-DM ($t(28) = -13.75$, $p < 0.001$; $t(28) = -15.37$, $p < 0.001$), and VT-visD groups ($t(28) = -14.42$, $p < 0.001$; $t(28) = -16.97$, $p < 0.001$). The same pattern occurred for the second practice block, P2, which showed fewer direction switched for VT and VT-CM compared to VT-CMDM ($t(28) = -10.54$, $p < 0.001$; $t(28) = -10.54$, $p < 0.001$), VT-DM ($t(28) = -11.72$, $p < 0.001$; $t(28) = -11.72$, $p < 0.001$), and VT-visD ($t(28) = -13.20$, $p < 0.001$; $t(28) = -13.20$, $p < 0.001$).

Importantly, training condition was critical during the test blocks. Performance during the first test block, T1, showed fewer joystick direction switches for VT compared to VT-DM ($t(28) = -2.72$, $p = 0.01$) and VT-visD ($t(28) = -2.05$, $p = 0.05$). Performance during the second test block, T2, showed fewer joystick direction switches for the no disturbance training conditions

VT and VT-CM compared to the disturbance training condition VT-DM ($t(28) = -2.58$, $p = 0.02$; $t(28) = -27$, $p = 0.03$).

To summarize the joystick direction switching measure, the number of compensatory movements (changes in joystick direction) was much smaller for the no-disturbance groups compared to the disturbance groups during training (P1 and P2). At test, the no-disturbance training groups increased their number of joystick direction switches to compensate for the introduction of disturbance motion, however, this did not reach the level of groups who trained with disturbance motion.

DISCUSSION

The need for motion in flight simulation has been studied extensively, but many of the results are conflicting. Some researchers have found evidence supporting the benefits of motion in simulation (Lee & Bussolari, 1989; McDaniel, Scott, & Browning, 1983; Van der Pal, 1999), while others have found the contrary (Bürki-Cohen et al., 2001; Go, Bürki-Cohen, and Soja, 2000; Jacobs & Roscoe, 1975; Koonce, 1979; Woodruff et al., 1976). We explored the hypothesis that disturbance cues (e.g. turbulence) are critical components contributing to the beneficial effects of training with self-motion (de Winter et al, 2012).

Participants performed a simple target tracking task within a motion simulator. Operation of a real moving vehicle involves correlated motion (e.g. in response to the operator's actions), turbulence (e.g. low frequency noise due to outside forces such as wind), and vibration (e.g. medium frequency noise due to motor vibration). The motion simulator models this system by calculating output forces (vehicle motion) in response to input forces (joystick displacement), and injecting noise into the system to simulate turbulence and vibration (disturbance motion).

Training occurred in one of five conditions, each of which involved a subset of the motion simulation parameters. Two conditions involved training without disturbance motion (VT and VT-CM), and three conditions involved training with disturbance motion (VT-CMDM, VT-DM and VT-visD). All participants were then tested on the target tracking task with the full motion model including correlated motion and disturbance motion (VT-CMDM).

Looking at the proportion of successfully tracked targets, we found evidence for differences in transfer of training across the groups. Accuracy improved for all conditions during the training phase, but only the disturbance groups demonstrated no decrease in accuracy at test, which suggests a positive transfer of training effect. When moving from training to test, the no-disturbance groups showed a significant reduction in accuracy. However, during the test phase their accuracy was no worse than those who trained with disturbance, so it is difficult to make strong conclusions with this measure alone. One interpretation is that the decrement in accuracy for the no disturbance groups was simply due to the high level of accuracy they were able to achieve during training, compared to the more challenging disturbance motion conditions. Moreover, there were no differences between the training groups in terms of speed; all groups showed similar practice effects on target track time across the four blocks.

According to the speed and accuracy observations then, it may not matter whether training involves disturbance motion or not. However, the more critical observations may be in other measures. Training with disturbance motion led to qualitatively different joystick control strategies, which persisted from training into test, and may provide some support for the benefit of training with disturbance.

Training with disturbance vs. no disturbance

Joystick control strategies differed depending on type of training. Training with disturbance motion seemed to influence the amount of compensatory movements made by participants while completing the tracking task. Those in the disturbance groups showed relatively little change in the amount of joystick movements (extent of movements and number of direction switches) across the experiment, with a reduction in the amount of movement over the practice blocks, but no change from practice to test, or across test blocks. Those in the no-disturbance training conditions made considerably fewer joystick movements in the training phase than those in the disturbance training conditions. During test, when the full motion model was encountered including correlated and disturbance motion, the magnitude of joystick movements and direction switches made by those in the no-disturbance training conditions approached (but did not always reach) the levels of the disturbance groups. Training with disturbance seems to encourage subjects to adopt a strategy in which they make many compensatory movements to adjust for disturbance. By the time they get to test, they are well practiced in this strategy. This may produce benefits for accuracy, or it may produce benefits in ways that we do not test in this study, for example, they may be more able to compensate for large, unexpected vehicle movements. In comparison, subjects in the no-disturbance condition use smoother joy stick movements during training, as there is no need to compensate for disturbance. During the test phase, they seem to persist in this strategy. Although they are forced to start making more compensatory movements (as evidenced by the increase in joystick movements from practice to test), it is unknown whether they would reach the performance level of those who trained with disturbance.

It is not yet clear what mechanism participants used to compensate for disturbance; whether they learn to ignore or actively compensate for motion disturbances when they experience them. If individuals are able to ignore disturbance motion, they may take a more relaxed approach to joystick control using a less tight grip and providing more slack. If individuals use a more active approach to compensation, an individual may impose more control over the joystick by attending to disturbances and retroactively compensating for them in order to stay on track. Both strategies could result in comparable amounts of joystick movements (as both are sensitive to disturbance) and it may be that those who train with disturbance learn one strategy while those who train without disturbance use the other. Future studies will examine these possibilities.

Types of disturbance

We used three different disturbance conditions (VT-CMDM, VT-DM, VT-visD). The first, correlated motion with disturbance motion, is the type typically used in transfer of training studies, as it is the closest to mimicking real world scenarios (de Winter et al, 2012). This is the condition that we used at test. One might expect that this condition would show the greatest benefit of practice, as subjects are performing the same task across 4 blocks. The other two disturbance motion training conditions isolated disturbance motion (VT-DM), and went further to isolate the visual effect of disturbance motion, by injecting the disturbance forces into the system but turning the movement of the motion platform off (VT-visD). That is, is the combination of correlated and disturbance motion required to provide a benefit, or is disturbance alone (disturbance motion or just the visual component of disturbance motion) enough to produce benefits in transfer of training. We found similar task performance and joystick control strategies across all three types of disturbance motion training.

Most interesting to us was the effectiveness of the isolated visual disturbance. This finding is particularly important because the VT-visD training condition does not require a motion platform. If visual disturbance is enough to elicit improvements in the test phase of our task, then it is possible that expensive motion simulators are not necessary for training. This condition has never been examined in isolation before. Here we find that it just may be the key to cost-effective training in simulated environments.

Limitations and Extensions

The effect motion had on training may be limited in our experiment by the task and the environment we used. In our current experiment, the visual display is presented in two-dimensions while the motion experienced by participants occurs in three-dimensional space. One could argue that this may have created an environment with an inherent perceptual conflict. Additionally, our task environment was not perceptually similar to how motion is experienced normally in day to day life. One way to address issues of structural and functional fidelity is to use realistic motion and environments. To retain structural fidelity, a simulation of motion would need to recreate motion that is perceptually normal or as similar as possible to how motion is experienced in everyday life. In addition, functional fidelity can be achieved through recreating realistic movements that are not fixed along specific axes (i.e. laterally from left to right). Allowing an individual to freely move in a three dimensional environment would more closely recreate vehicular motion. We recommend that follow up experiments should recreate a similar target pursuit task in a three-dimensional environment. In such a task, the targets could be suspended in three-dimensional space within a realistic simulated environment that includes features like ground (e.g., grass, trees etc.) and sky (e.g., clouds) which would provide points of reference and allow for optic flow. It may also be useful to include subjective reports, as this can be instrumental in gauging a participant's experience regarding the fidelity of motion.

Our results are also limited to measuring the effects of low-frequency low-level disturbance motion on transfer-of-training, and may not necessarily extend to low-frequency, high-level disturbances (e.g., wind shears that present more intense forces). This is common within the literature, which lacks empirical measures of disturbance training in low-frequency high-level disturbances.

Conclusion

We have found evidence that training with disturbance motion facilitates transfer-of-training to test conditions relative to training without disturbance. Interestingly, we also found that a visual representation of disturbance that does not use the motion platform may function as effectively as disturbance applied to the entire motion platform with respect to transfer-of-training effects. This finding warrants further exploration as it may finally answer the question posed by Hopkins in 1975 when discussing the cost/benefits of motion simulators: "How much should you pay for that box?" It may be the case that as long as visual disturbance cues retain their fidelity to test situations, a simple presentation screen rather than entire simulator can be used in training. Moving forward, we recommend replicating the current study using a three-dimensional virtual environment in which participants experience a more immersive simulation that is more similar to realistic motion. Training with motion in three-dimensions may reduce the observed benefit of simple visual disturbance, and possibly favour an immersive self-motion environment for the transfer-of-training.

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FIGURE CAPTIONS

Figure 1: The visual display as seen by the participant consisted of a blue background with clouds, a crosshair (white cross at the center of a red square) and a target (blue circle). **A:** At the beginning of each trial, the crosshair was displayed at the centre of the screen while the target was positioned to the left of right of the crosshair. **B:** Subjects were instructed to move the crosshair (which remained fixed to the centre of the screen) so that it is centred over the target circle.

Figure 2: A diagram showing the input to the motion platform and to the visual display screen, as filtered through the position model (which determines the position of the crosshair on the screen) and the force model (which determines how the motion platform moves). Input from the joystick represents the actions of the participant. Vibration noise represents small medium-frequency movements that mimic engine and vehicle vibration (this also masks all noises coming from the mechanical and moto components of the motion platform). Turbulence represents medium to large forces that "push" the vehicle off course. Each of switches A B and C could be "off" or "on" resulting in the five practice conditions. For example, when all switches were on (VT-CMDM) there was correlated motion (C on) with turbulence (A and B on). In comparison, when the motion platform was turned off (B off), the visual display was presented with turbulence (VT-visD).

Figure 3: A depiction of 5 trials (3 seconds each) showing the relative position of the target, the joystick, and the crosshair. Within a given trial, the joystick and crosshair begin in the starting position. The initial movement of the joystick triggers the movement of the crosshair toward the target. **Trial 1**: Not tracked, the crosshair does not reach the position of the target for the required duration (500 ms). **Trial 2 and 3**: Tracked, the crosshair successfully reaches the location of the target for the require duration. **Trial 4**: Not tracked, the cross hair overshoots the target. This also depicts the error integral, which is the area from the position of the crosshair relative to the position of the target. **Trial 5:** Not-tracked, the initial joystick movement is away from the target, this is corrected, but not in time to successfully track the target.

Figure 4: Mean accuracy as a function of training condition across practice and test blocks. Bar shading distinguishes training with disturbance motion from training without disturbance motion. Test blocks presented the full motion model (VT-CMDM). Error bars represent standard error. *P1*= practice block 1, *P2* = practice block 2, *T1* = test block 1, *T2* = test block 2. *VT* = visual tracking task only, *VT-CM* = visual tracking task with correlated motion, *VT-CMDM* = visual tracking task with correlated motion and disturbance motion, *VT-DM* = visual tracking task with disturbance motion, *VT-visD* = visual tracking task with visual disturbance.

Figure 5: Mean target track time as a function of training condition across practice and test blocks. Bar shading distinguishes training with disturbance motion from training without disturbance motion. Test blocks presented the full motion model (VT-CMDM). Error bars represent standard error. *P1*= practice block 1, *P2* = practice block 2, *T1* = test block 1, *T2* = test block 2. *VT* = visual tracking task only, *VT-CM* = visual tracking task with correlated motion, *VT-CMDM* = visual tracking task with correlated motion and disturbance motion, *VT-*

DM = visual tracking task with disturbance motion, *VT-visD* = visual tracking task with visual disturbance.

Figure 7: Average amount of joystick movements made (as measured by the joystick movement index) as a function of training condition across practice and test blocks. Test blocks presented the full motion model (VT-CMDM). Error bars represent standard error. *P1*= practice block 1, *P2* = practice block 2, *T1* = test block 1, *T2* = test block 2. *VT* = visual tracking task only, *VT-CM* = visual tracking task with correlated motion, *VT-CMDM* = visual tracking task with correlated motion and disturbance motion, *VT-DM* = visual tracking task with disturbance motion, *VT-visD* = visual tracking task with visual disturbance.

Figure 8: Average number of times the joystick changed direction as a function of training condition across practice and test blocks. Test blocks presented the full motion model (VT-CMDM). Error bars represent standard error. *P1*= practice block 1, *P2* = practice block 2, *T1* = test block 1, *T2* = test block 2. *VT* = visual tracking task only, *VT-CM* = visual tracking task with correlated motion, *VT-CMDM* = visual tracking task with correlated motion and disturbance motion, *VT-DM* = visual tracking task with disturbance motion, *VT-visD* = visual tracking task with visual disturbance.

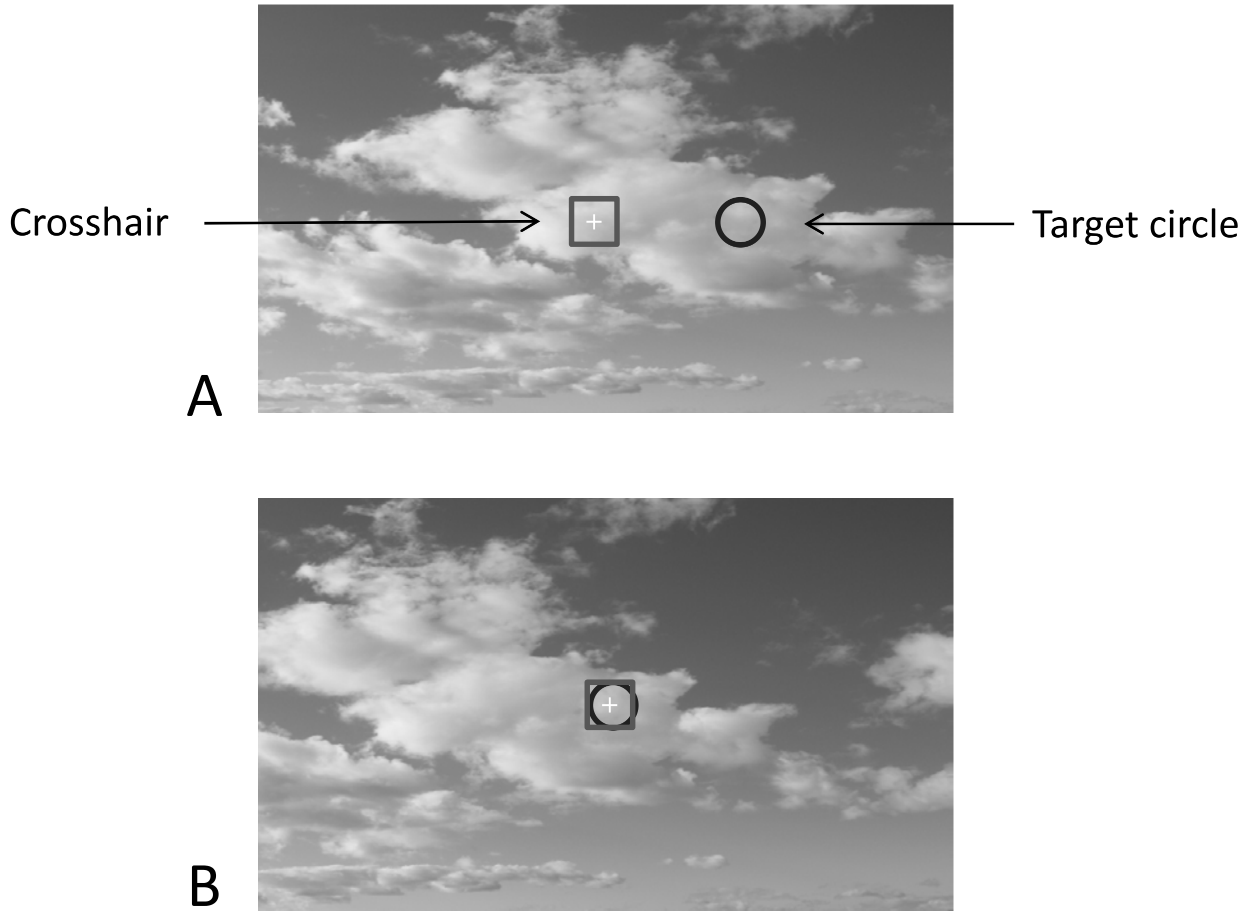
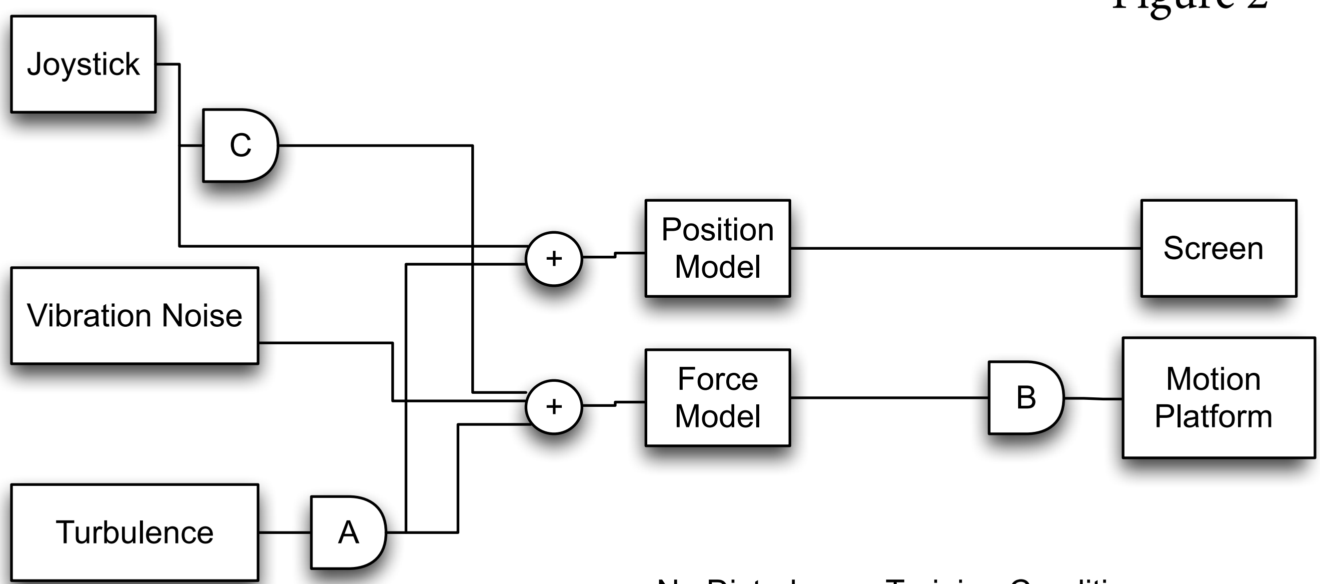


Figure 1

Figure 2

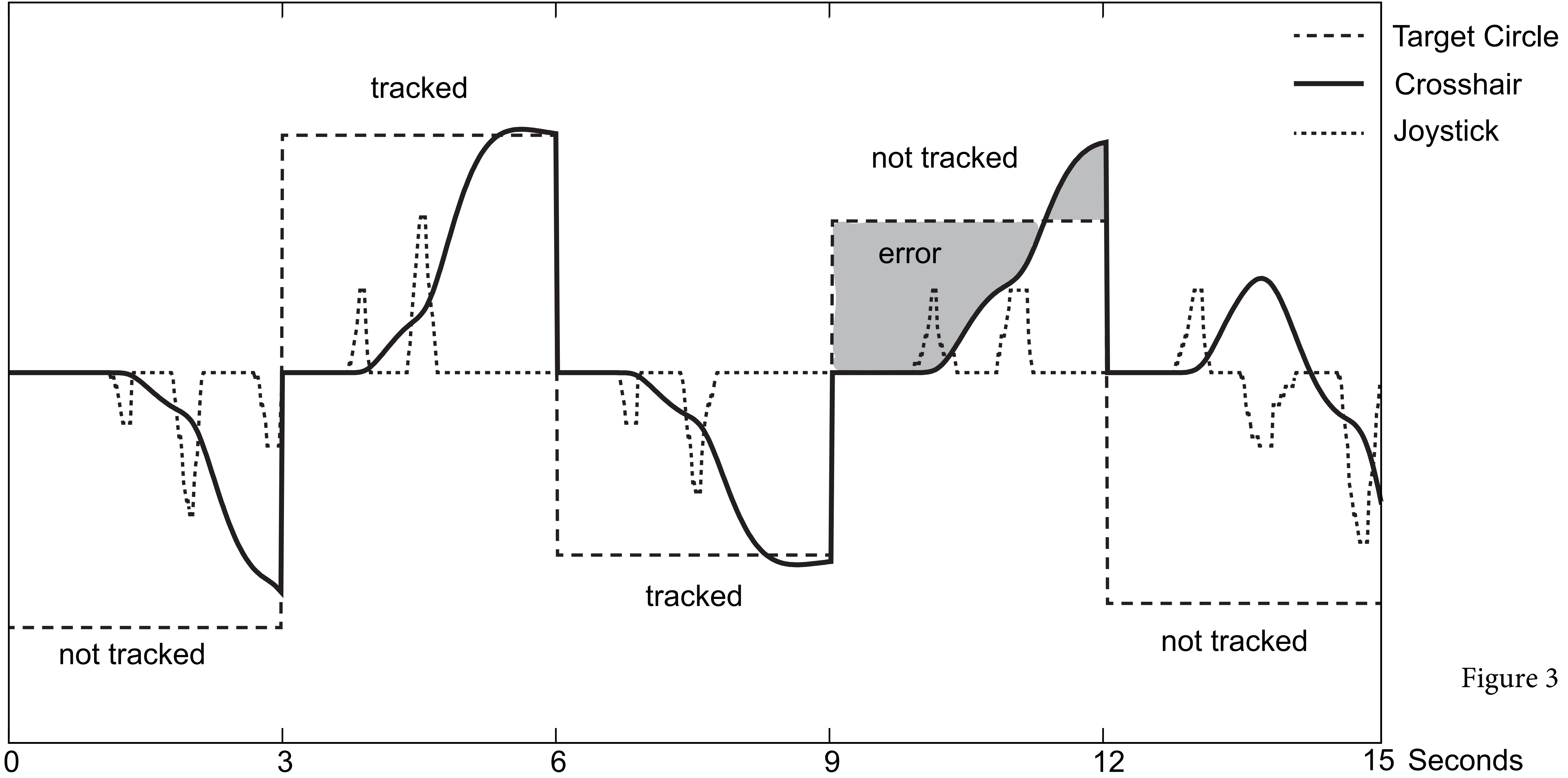


Switch A: turn turbulence on
Switch B: turn motion on
Switch C: enable correlated motion

No Disturbance Training Conditions:
VT OFF: A, B, C
VT-CM ON: B, C; OFF: A

Disturbance Training Conditions:
VT-CMDM ON: A, B, C
VT-DM ON: A, B; OFF: C
VT-visD ON: A; OFF: B, C

Test Condition:
VT-CMDM ON: A, B, C


Target Circle
Crosshair
Joystick
tracked
not tracked
error
tracked
not tracked
not tracked
0
3
6
9
12
15 Seconds
Figure 3

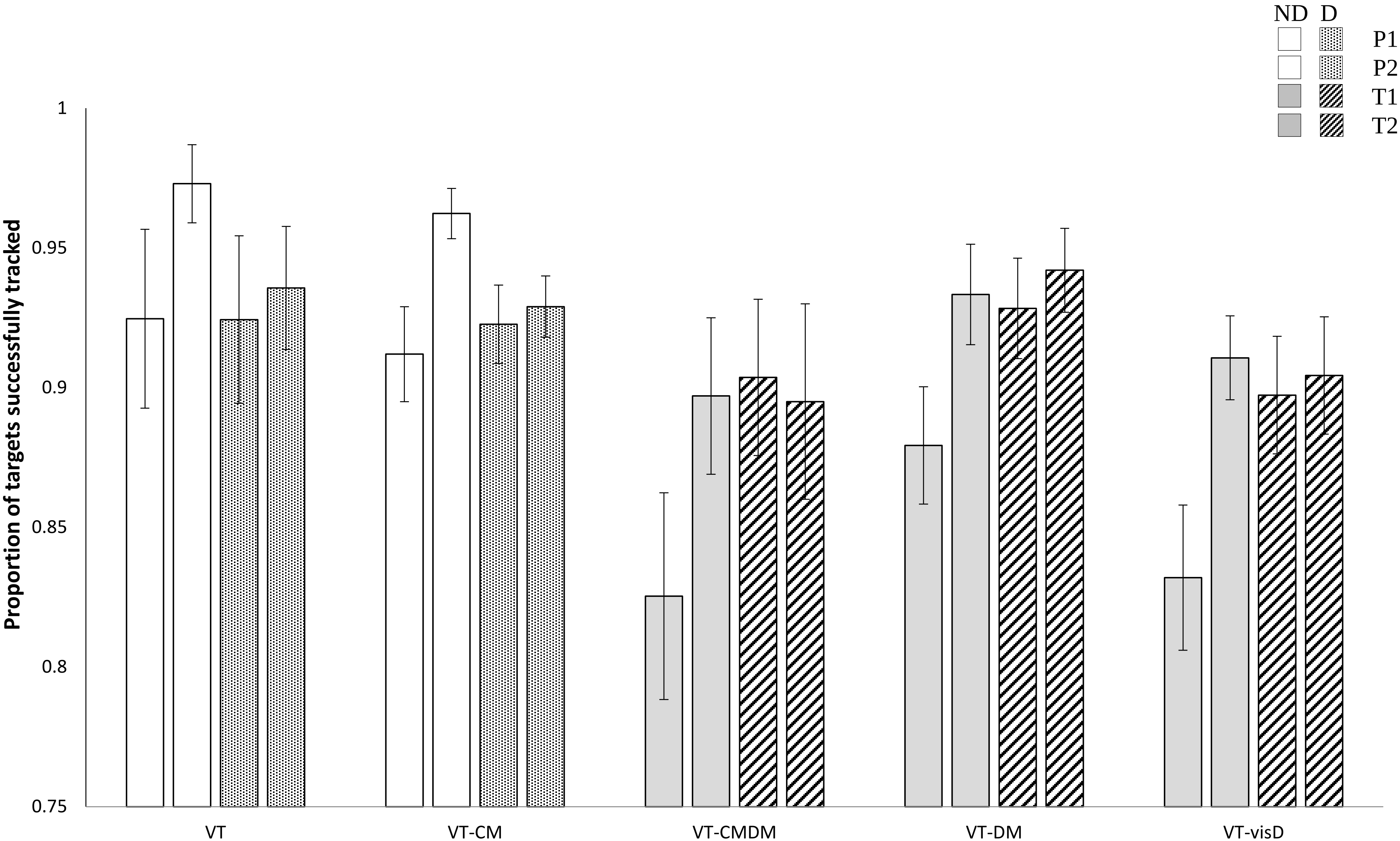
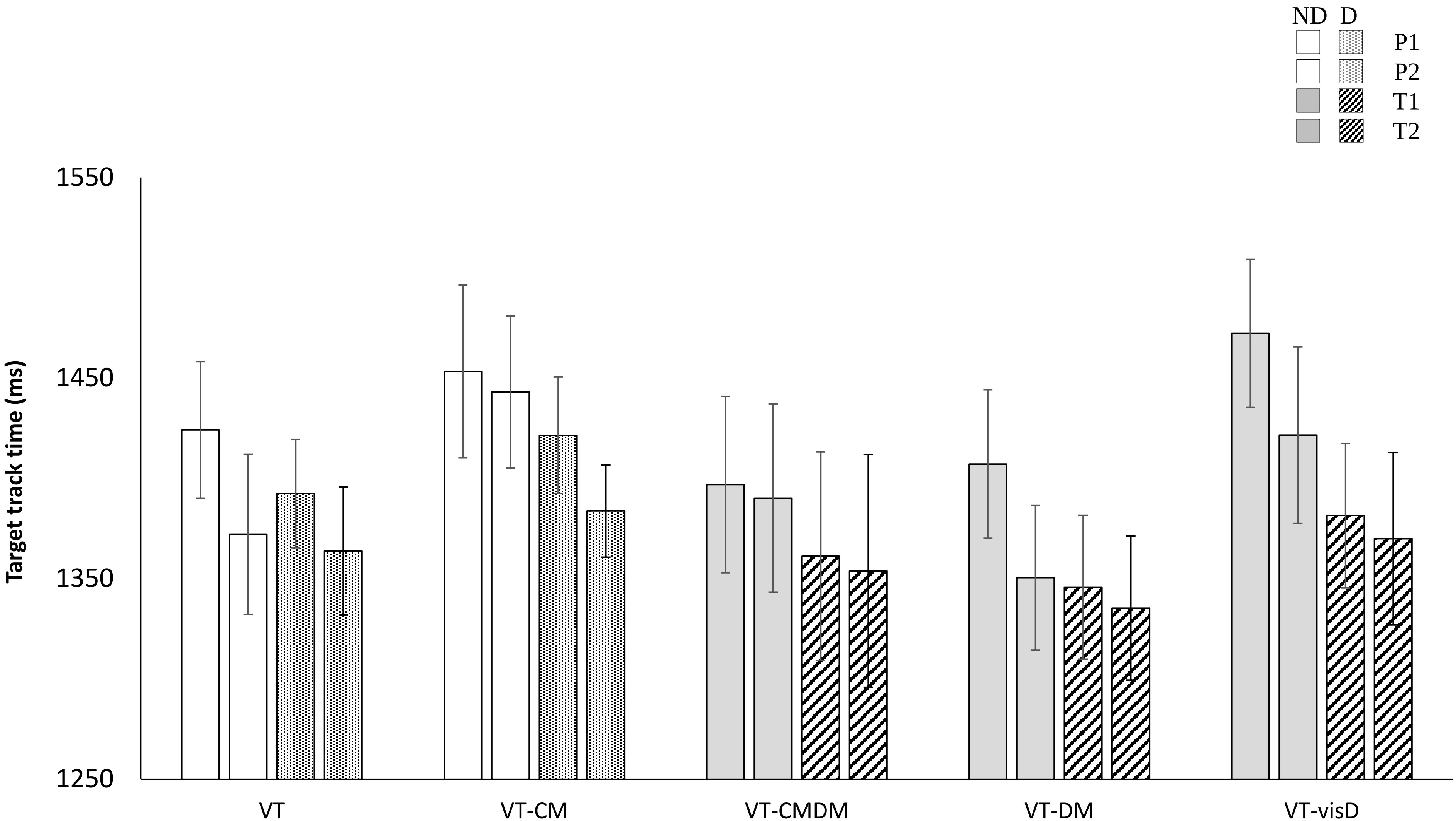

ND D
P1
P2
T1
T2
1
0.95
0.9
0.85
0.8
0.75
Proportion of targets successfully tracked
VT
VT-CM
VT-CMDM
VT-DM
VT-visD

Figure 4



ND D
P1
P2
T1
T2
1550
1450
1350
1250
Target track time (ms)
VT
VT-CM
VT-CMDM
VT-DM
VT-visD

Figure 5

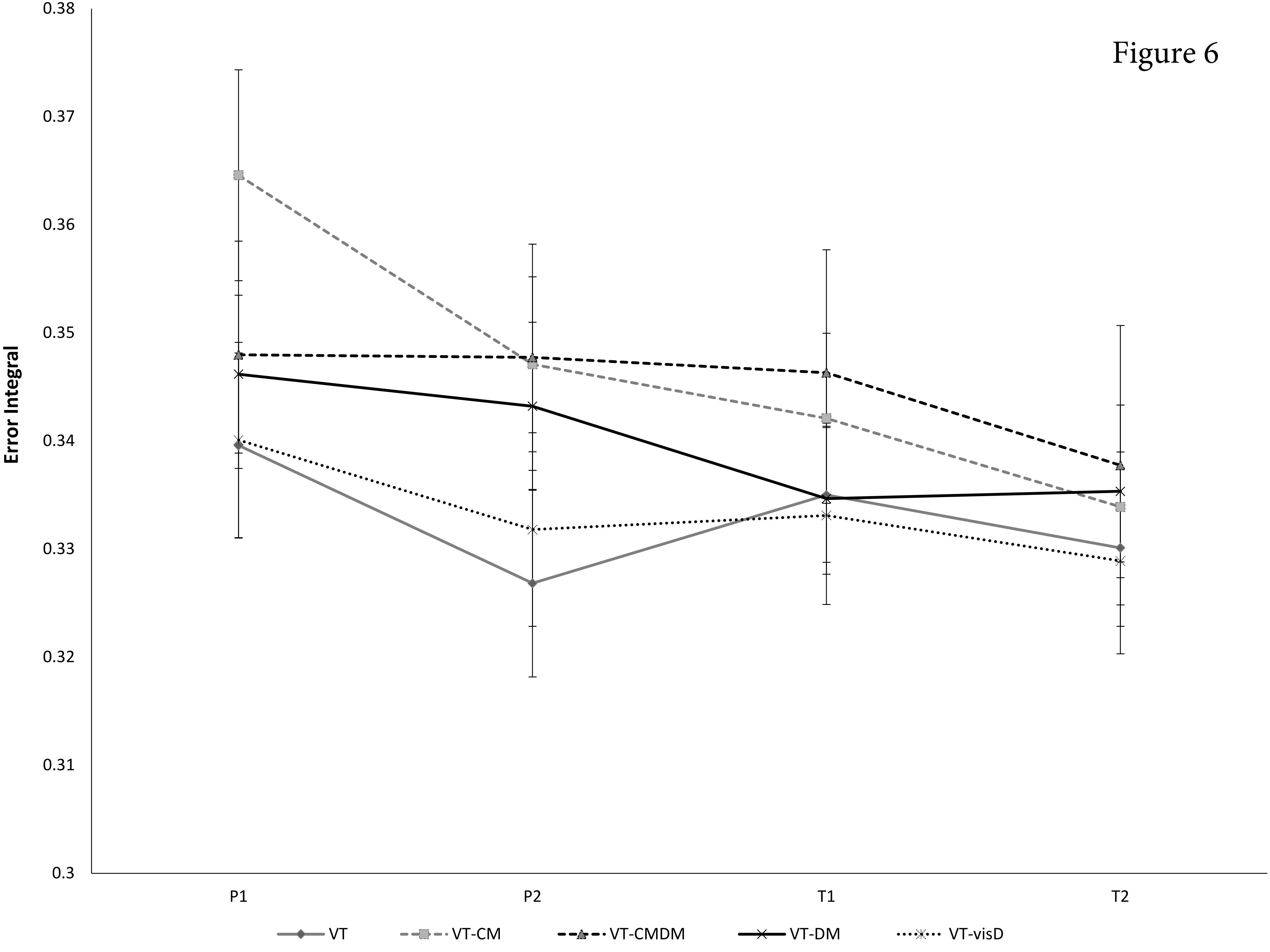


Figure 6
Error Integral
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
0.3
P1
P2
T1
T2
VT
VT-CM
VT-CMDM
VT-DM
VT-visD

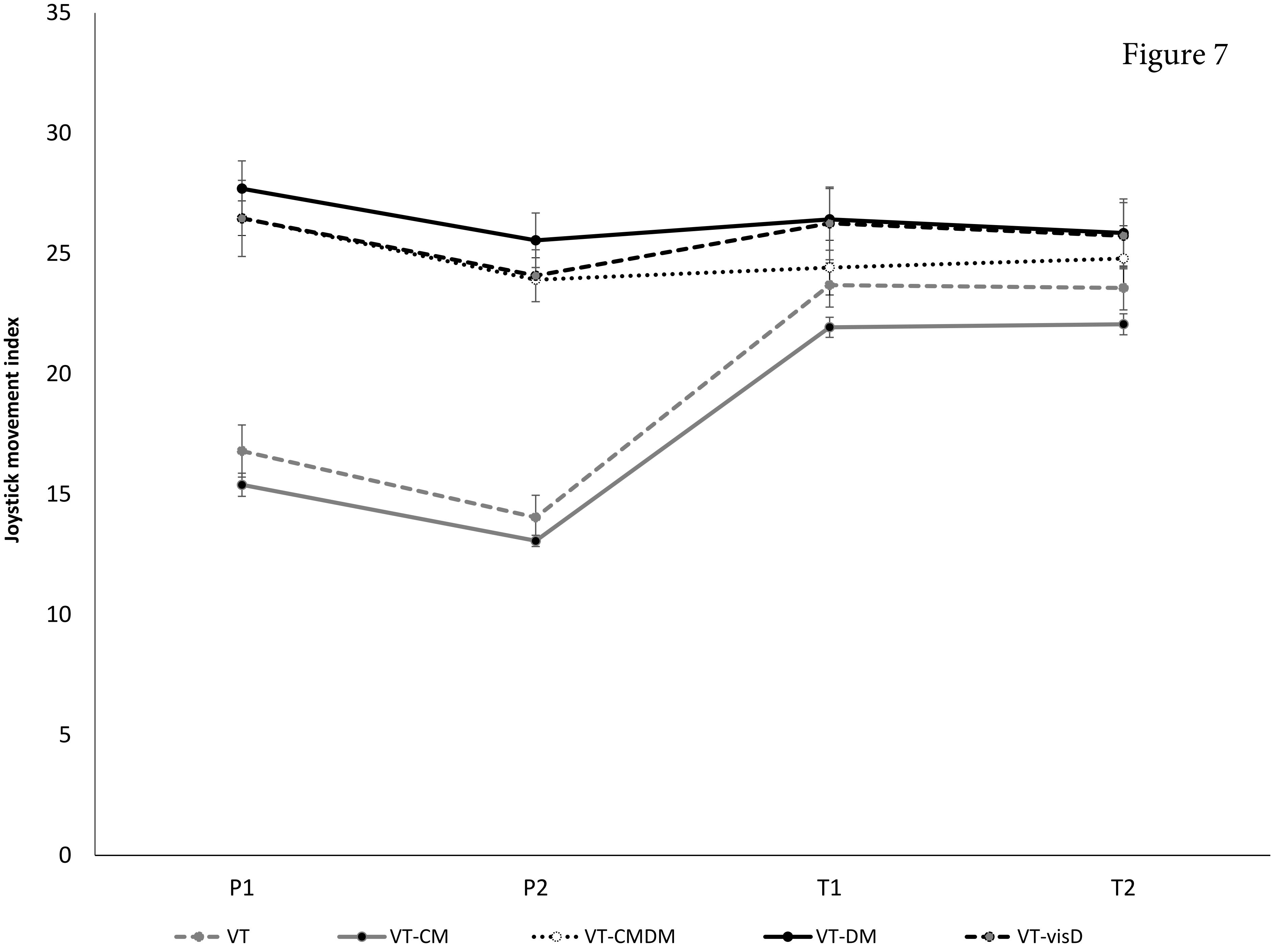


Figure 7
Joystick movement index
35
30
25
20
15
10
5
0
P1
P2
T1
T2
VT
VT-CM
VT-CMDM
VT-DM
VT-visD

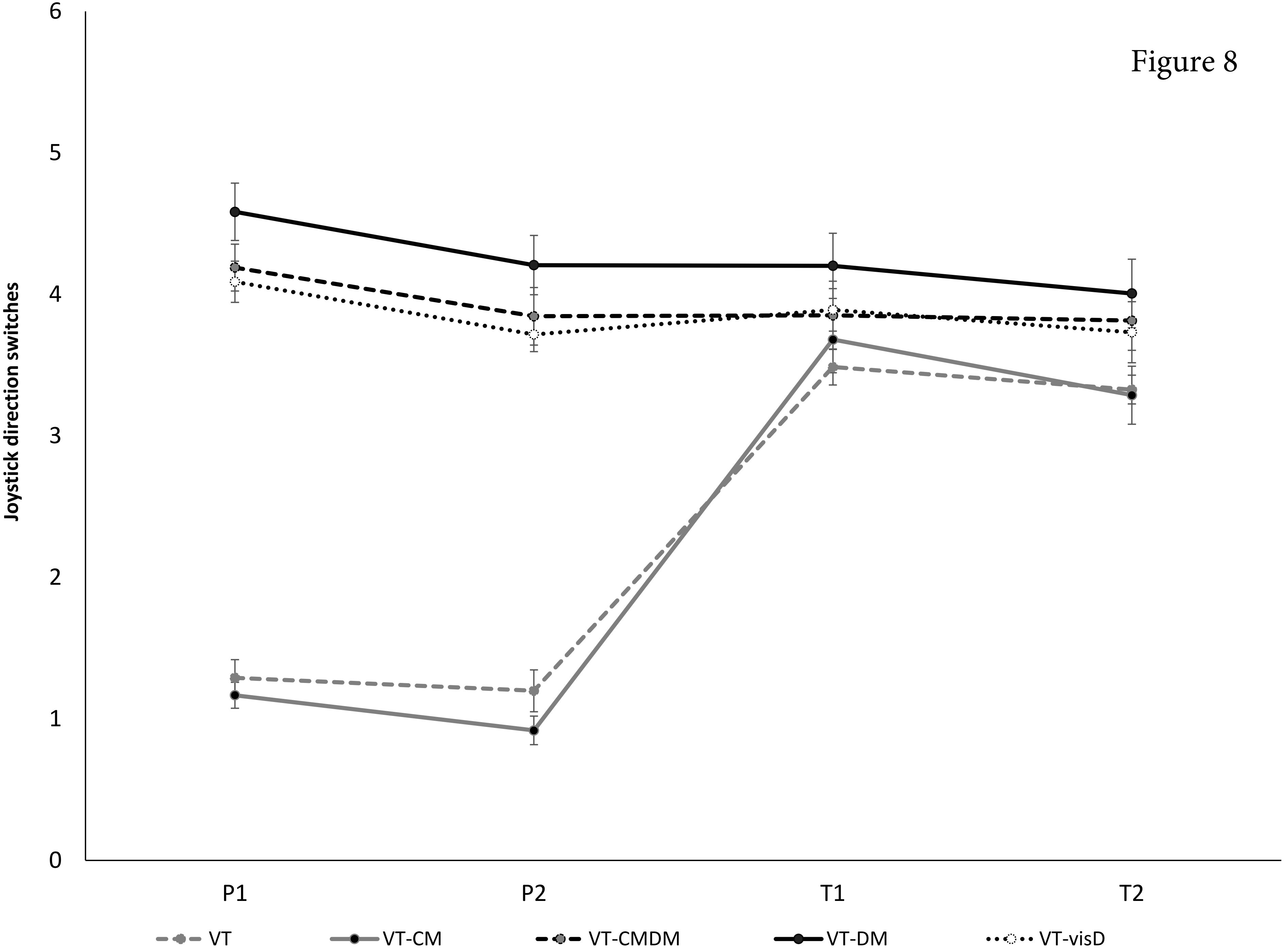


Figure 8
Joystick direction switches
6
5
4
3
2
1
0
P1
P2
T1
T2
VT
VT-CM
VT-CMDM
VT-DM
VT-visD