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# The effects of dividing attention on smooth pursuit eye tracking

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**Running Head:** Smooth Pursuit and Attention

**Abstract:**

Attentional processes have traditionally been closely linked to the production of saccadic eye movements, but their role in the control of smooth pursuit eye movements remains unclear. In two experiments we used dual task paradigms to vary the attentional resources available for pursuit eye tracking. In both experiments we found that attentionally demanding secondary tasks impaired smooth pursuit performance, resulting in decreased velocity and increased position error. These findings suggest that attention is important for the maintenance of accurate smooth pursuit, and do not support the hypothesis that pursuit is a relatively automatic function that procedes optimally in the absence of attentional control. These results add weight to the suggestion that a similar functional architecture underlies both pursuit and saccadic eye movements.

**Descriptor Items:** Smooth Pursuit, Eye tracking, Attention, Dual task, Divided attention.

**The effects of dividing attention on smooth pursuit eye tracking**

Human and non-human primates use both saccadic and smooth pursuit eye movements to ensure that the image of an object of interest falls and remains on or near the fovea. These two types of eye movements, and the neural systems involved in their control, have generally been considered separately by researchers. According to traditional views, smooth pursuit is controlled by a relatively simple cortico-pontine-cerebellar pathway, linking visual sensory areas involved in the processing of motion signals to motor regions the cerebellum, via the pontine nuclei (PN) (Ilg, 1997). In keeping with this comparatively simple neural architecture, pursuit is often considered as a relatively automatic “visual reflex”. Saccadic eye movements on the other hand can be triggered by a variety of different signals, both internal and external, and are generally thought of as a more volitional behaviour involving a more complex neural circuit (Pierrot-Deseilligny, Muri et al., 2003; Schall, 1995; Wurtz, 2000). This circuit includes direct projections from higher cortical areas such as the supplementary eye fields (SEF) and dorsolateral prefrontal cortex (DLPFC) to oculomotor structures in the brainstem including the superior colliculus (SC)(Shook, Schlag-Rey et al., 1990;Selemon and Goldman-Rakic, 1988). The SC also receives indirect projections from these cortical areas via structures in the basal ganglia (Hikosaka, Takikawa et al., 2000).

One consequence of the view that saccades represent a more volitional and controlled type of behaviour than smooth pursuit, is that research into the role of attention in oculomotor control has generally focussed on saccadic eye movements. There is an extensive literature detailing the close relationship between saccadic eye movements and visual attention (See e.g. Corbetta, Akbudak et al., 1998; Deubel & Schneider, 1996; Findlay and Walker, 1999; Sheliga, Riggio & Rizollatti, 1995; Shepherd, Findlay & Hockey, 1986), but comparatively few studies have explored the role of attention in smooth pursuit eye movements. Those that have tend to focus on the role of attention in pursuit initiation (e.g. Ferrera & Lisberger, 1995; Knox and Bekkour, 2002; Recanzone and Wurtz, 2000). These studies demonstrate that attention plays a role in selecting the target for pursuit, but its role during pursuit itself remains unclear.

Recent research has begun to challenge the traditional view that pursuit and saccadic eye movements are subserved by largely distinct neural systems. Krauzlis (2004) argues convincingly that it may be more useful to consider pursuit and saccadic eye movements as being two different outcomes from a “shared cascade of sensory-motor functions”, with significantly overlapping neural substrates. According to this reconceptualisation, attention may play a far greater role in the control of smooth pursuit eye movements than has traditionally be supposed. In support of this argument, converging lines of evidence suggest that neurons in cortical regions beyond MT/MST are involved in the control of pursuit. For example, stimulation of neurons in the SEF facilitates anticipatory pursuit (Missal & Heinen, 2004) in primates, and functional imaging studies in humans have demonstrated a distinct subregion of the FEF is activated during pursuit (e.g. Petit & Haxby, 1999).

The few studies that have explored the role of attention during pursuit maintenance have produced conflicting results. Some recent research appears to support the notion that smooth pursuit is a relatively automatic behaviour. In an important study, Kathmann et al (1999) measured smooth pursuit performance in a group of healthy controls during single and dual task conditions. In the dual task conditions, subjects tracked a pursuit target with their eyes whilst simultaneously performing an auditory discrimination task. The rationale behind this approach is that in the dual task conditions, attentional resources must be allocated to the auditory discrimination task. If smooth pursuit and the auditory discrimination share a common attentional resource, then performing the discrimination task should result in reduction in smooth pursuit performance. In fact, the authors found that both dual task conditions led to considerable improvements in smooth pursuit performance compared to the single task condition. The authors explained the finding by arguing that pursuit eye tracking is a highly automatic process, one that is actually performed most efficiently in the absence of controlled attention. In other words attempting to consciously control automatic behaviours can be counter-productive (see also Baumeister, 1986; Lewis & Lindberg, 1997).

Although one other study employing dual task methodology also found that performing a secondary task led to improved smooth pursuit (Van Gelder, Lebedev et al., 1995), several other studies have found that secondary tasks can lead to varying degrees of impairment. For example, an early study found that counting backwards in 7s or 13s led to increases in blinks, saccadic eye movements and “non-tracking episodes” during pursuit, although the sample size was small (N=10) and only the increase in blinks reached statistical significance (Brezinova and Kendell, 1977). Similarly, Acker & Toone (1978) found that counting backwards led to impairments in pursuit performance in an equally small group of healthy controls (pursuit performance was measured using qualitative ratings). Other studies have reported mixed findings – for example Lipton et al (1980) found that counting backwards led to a significant increase in the number of “velocity arrests” in healthy controls, but a non-significant increase in qualitative ratings of pursuit.

More recent research also suggests attention plays a significant role during pursuit. For example, Van Donkelaar & Drew (2002) have demonstrated that reaction times to changes in stimuli are reduced if they occur 1-2 degrees in front of the actual pursuit target, but increased if they occur 1-2 degrees behind, suggesting that allocation of attention is biased to a position slightly in front of the target during pursuit. Chen & Holzman (2002) found that performing a brief secondary task (judging which of two horizontal gratings presented above and below the pursuit target has the higher spatial frequency) at the same time or 450 ms after pursuit onset led to impairments in the maintenance of pursuit.

The early studies tended to use unsophisticated oculographic recording techniques such as electrooculography (EOG) and relatively crude qualitative ratings of smooth pursuit performance. However, together with the recent research described above, they do suggest that the role of attention in the control of smooth pursuit eye movements is not clearly established, and that the nature of the secondary task may be an important determinant of the type of effect observed.

Attention is not a unitary construct (Allport, 1993; Pashler, Johnston & Ruthruff, 2001), and it is possible that some secondary tasks may lead to impairments and others lead to improvements, depending on the nature of the attentional resources they require, and the involvement of these resources in smooth pursuit function.

In two experiments, we used video-based oculographic recording and quantitative analysis techniques to determine the extent that secondary tasks that draw on different aspects of attentional processing impair or improve smooth pursuit eye tracking. One critical property of attention is that it can be directed to specific positions in space (Posner & Driver, 1992). If attentional resources do have a role to play in the control of smooth pursuit eye movements, those concerned with the localisation of information within external space might be expected to be particularly relevant. In Experiment 1 we compared the effect of performing concurrent spatial and non-spatial auditory discrimination tasks on smooth pursuit performance. There is an extensive literature detailing cross modal interactions in spatial attention (e.g. Colonius & Arndt, 2001; Driver and Spence, 1998), particularly between vision and audition. These interactions extend to the control of eye movements. For example, the latencies of saccadic eye movements to spatial locations are reduced if visual and auditory stimuli occur at the same spatial location (Hughes, Reuter-Lorenz et al., 1994; Munoz and Corneil, 1995). We hypothesised that a secondary task involving attention to spatial locations in the acoustic domain would disrupt pursuit performance to a greater extent than a secondary task with no spatial component. In a second experiment we explored the effect of task difficulty, and used secondary tasks that did not involve auditory discrimination.

## Experiment 1: The effects of spatial vs non-spatial tone discrimination tasks on smooth pursuit eye movements.

### Methods

*Participants*

Forty healthy individuals participated in this experiment. The volunteers were all students at Sussex University who participated for course credit. 8 Males and 32 females took part. Their mean age was 21.4. Exclusion criteria included a current personal history of any psychotic or neurological illness. Data from two female participants was not included as they failed to understand the task instructions and made virtually no smooth eye movements in any of the conditions.

*Apparatus*

Eye movements were recorded with an SR-Research Eyelink II eye tracker. This device has a high spatial resolution and a sampling rate of 500Hz. Three cameras simultaneously record the position of both eyes and the head, allowing gaze position to be computed without the need to restrain head movements.

All participants were tested in a dimly lit quiet room. They sat in a height-adjustable office chair that has been modified to prevent any rotation about the vertical axis. Participants viewed a 21-inch ViewSonic monitor from a distance of 60 cm, which subtended a visual angle of 40 degrees horizontally and 30 degrees vertically. The display was generated using an nVidia graphics card and the frame rate was 100 Hz.

In two conditions participants pursued the target whilst simultaneously performing an auditory discrimination task. In both tasks the auditory stimuli were recorded onto CDs and presented via binaural headphones.

*Procedure*

A three-point horizontal-only calibration was performed at the start of the experiment, followed by a three-point calibration accuracy test. Calibration was repeated if the error at any point was more than 1.0 degree or if the average error for all points was greater than 0.5 degrees. All recordings were taken from the eye that produced the most accurate calibration.

Pursuit stimuli were presented on the computer screen, and consisted of a red circle presented against a black background. The circle subtended approximately 0.5 degrees of visual angle and starting on the left moved horizontally backwards and forwards +/- 27 degrees. Two blocks of 6 cycles of constant velocity pursuit were generated. Each block was preceded by a drift correct procedure that lasted approximately 3 seconds. In the first block the target moved at a constant velocity of 0.25Hz and in the second block the target moved at a constant velocity of 0.5Hz.

Subjects tracked the target in three different experimental conditions: 1) in the absence of any secondary task (single task control condition), 2) whilst performing pitch discrimination task and, 3) whilst performing a spatial discrimination task. The stimuli for conditions 2 and 3 consisted of 200ms tones presented with an interstimulus interval of between 800 and 1200 msec. In the "Pitch" task the tones were either 200Hz ("low") 500 Hz (Medium) or 1000 Hz(High). Before the dual task condition started participants were played a 30 second sample of the 3 different tones cycling from low through medium to high, in order to familiarise themselves with the pitches and their labels. In the experimental task the tones varied pseudorandomly, such that no more than two of the same tone occurred in sequence. In the spatial task, the tones were all 500Hz, and were presented either monaurally to the left and right ears, or binaurally (giving a percept that the sound is located in the middle of the head). Participants were played a 30 second sample of the tones cycling from left through middle to right in order to familiarise themselves with the tones and their labels ("Left", "Middle" and "Right"). For both secondary tasks participants were required to respond verbally to each tone with its appropriate label. The secondary tasks were performed continually whilst tracking the pursuit target.

*Data analysis*

Eye movements were analysed using custom software written in LabVIEW. After converting the output to Ascii, the software read in the eye position data which consists of a series of X-axis pixel co-ordinates sampled every 2 ms. The software simultaneously displayed the horizontal position of the eye and the pursuit target. In order to avoid acceleration and deceleration transients pursuit measurements were taken from the middle 50% of each ramp. Within this portion, the operator used two cursors to define the beginning and end of all periods of pursuit. Non-pursuit consisted of intrusive or corrective saccades, blinks or fixations (such as can occur after an anticipatory saccade before a corrective back-up saccade is made). Within each operator defined period of pursuit, the program calculated the velocity gain (ratio of eye velocity to target velocity) and the Root Mean Square Error (RMSE - the square root of the average position error). For each target speed a weighted average velocity gain was calculated (the gain and RMSE values were weighted by the duration of the sample they was taken from). We measured RMSE in order to provide comparability with previous reseach. We chose to also measure velocity gain as this provides a straightforward index of the smooth pursuit systems cardinal function - to match eye velocity to target velocity. RMSE values were log-transformed in order to reduce skewness.

## Results and Discussion

The average velocity gain for the two target speeds and three conditions is presented in figure 1a. Participants had lower gain when pursuing the faster target ($F(1,37) = 46.78$, $p < 0.001$). There was also a significant main effect of Condition ($F(2,74) = 11.93$, $p < 0.001$). The interaction between the two factors was not significant ($F(2,74) = 1.56$, ns). Planned comparisons revealed that velocity gain was reduced in both dual task conditions compared to the control condition ($ts(37) > 3.93$, $ps < 0.01$) and that these two conditions did not differ ($t(37) = 0.03$).

LogRMSE was increased at the faster target speed ($F(1.37) = 12.54$, $p < 0.001$, see figure 1b). The main effect of condition was also significant ($F(2,74) = 5.80$, $p < 0.01$). As there was no condition by speed interaction ($F(2,74) = 0.433$, $p = 0.65$), the main effect of condition was further explored using planned comparisons. LogRMSE was significantly higher in the non spatial dual task condition compared to the single task condition ($t(37) = -2.86$, $p < 0.01$) but the difference between the spatial dual task condition and the single task condition was not significant ($t(37) = -1.69$, $p = 0.1$).

Unlike Kathmann et al (1999) we found no evidence of secondary tasks improving smooth pursuit performance, as measured by both velocity gain and RMSE. In fact both the spatial and non-spatial secondary tasks led to significant reductions in gain compared to the single task condition, and increases in RMSE, although only the increase in the non-spatial condition was significant. These results suggest that smooth pursuit and the secondary tasks share some common processing resource.

We predicted that the spatial secondary task would impair pursuit performance more than a non-spatial secondary task, but the results did not support this prediction. In fact only the non-spatial secondary task led to significant increase in RMSE. One interpretation of this result is that smooth pursuit makes demands on general attentional resources as opposed to those involved specifically in localising information in a spatial frame of reference. Alternatively, cross-modal effects in attention are generally quite small, and it is possible that the spatial secondary task did not make sufficient demands on spatial attention to impact on performance.

Experiment 2 further explored the role of spatial and non spatial attention in smooth pursuit, using two different secondary tasks, one spatial (tapping a boustrophedon pattern on a key board) and one non-spatial (generating a sequence of random numbers). Pursuit performance in both dual task conditions were compared to a single task baseline, and two dual task control conditions, one involving single key presses, the other involving repeating the numbers 1 through 10. In order to increase the general task difficulty the target moved at 0.5 and 0.75 Hz in all conditions.

## Experiment 2: The effects of spatial vs non-spatial tapping, and random vs non-random number generation on smooth pursuit eye tracking.

### Methods

*Participants*

Sixteen healthy individuals participated in this experiment. The volunteers were all students at Sussex University who participated for course credit. 4 Males and 12 females took part. Their mean age was 20.8. Exclusion criteria included current psychiatric or neurological illness.

*Apparatus*

The apparatus was identical to that used in Experiment 1.

*Procedure:*

With the exception of the increased target speeds, the stimulus properties remained the same as in Experiment 1. The major difference concerned the nature of the secondary tasks used. In the current experiment, participants tracked the target in five different experimental conditions: 1) in the absence of any secondary task (single task control condition). 2) Whilst tapping a boustrophedon[1] pattern on the number pad of a computer keyboard (dual task tapping condition). 3) Whilst tapping a single key on the number pad of a computer keyboard (tapping control condition). 4) Whilst generating out loud a sequence of random numbers between 0 and 9 in time with metronome tone occurring once a second (dual task random number condition). 5) Whilst counting out loud sequentially from 1 to 10 in time with a 1Hz metronome tone (random number control condition).

**Results and Discussion**

The average velocity gain for the two target speeds and five conditions is presented in figure 2a. A 5 (condition) x 2 (target speed) repeated measures ANOVA revealed a significant main effect of speed, ($F(1,15) = 70.55$, $p < 0.001$), as participants again had lower velocity gain at the higher target speed. There was also a significant main effect of condition ($F(4,60) = 7.35$, $p < 0.02$), but no interaction between condition and target speed ($F(4,60) = 0.324$). In order to further explore the main effect of condition the data was collapsed over target speed, and planned comparisons performed. There was no significant difference between the single task control condition and either the random

[1] On a numberpad with the 1 at the bottom, a boustrophedon pattern consists of the following repeated sequence: 123654789654.

number control condition ($t(15) = 0.17$, $p = 0.86$) or the tapping control condition ($t(15) = 1.56$, $p = 0.14$). The difference between the random number control condition and the random number generation condition also failed to reach significance ($t(15) = 1.66$, $p = 0.11$). However, the difference between the tapping control condition and the boustrophedon tapping condition was highly significant ($t(15) = 3.5$, $p < 0.005$).

The log RMSE scores are presented in figure 2b, and mirror the pattern of results found for velocity gain. ANOVA revealed a significant main effect of speed, as log RMSE was greatest in the higher target speed. The main effect of condition was also significant ($F(4,60 = 4.14$, $p < 0.05$), and again there was no interaction between target speed and condition ($F(4,60) = 0.1$). The main effect of condition was explored by collapsing the data across target speed and performing planned comparisons. There was no significant difference between the single task condition and either the random number control condition ($t(15) = -1.64$, $p = 0.12$) or the tapping control condition ($t(15) = -0.45$, $p = .66$). Again, the difference between the random number control and random number generation condition was not significant ($t(15) = 0.06$, $p = 0.95$). The difference between the tapping control and boustrophedon tapping condition was significant ($t(15) = 3.17$, $p < 0.01$).

These results demonstrate that not all secondary tasks lead to impairments in smooth pursuit performance. Both the random number control condition (which involved repeatedly counting from 1 to 10 out loud) and the Spatial Tapping control condition (which involved tapping a single key in time with a metronome) did not lead to reductions in velocity gain or increases in RMSE. It is important to note that these less demanding secondary tasks still did not result in improvements in smooth pursuit. Increasing the target speed led to an overall decrease in gain values and increase in RMSE values compared to Experiment 1, so this failure is unlikely to be due to ceiling effects. Interestingly, the random number generation task did not lead to significant reductions in pursuit performance, whereas the spatial tapping condition did. This finding suggests that tapping a boustrophedon pattern and tracking a moving target may share some processing resources.

**General Discussion.**

The main finding across both experiments was that attentionally demanding secondary tasks led to impairments in smooth pursuit eye tracking as measured by a reduction in velocity gain and increase in RMSE. None of the secondary tasks led to improvements in pursuit performance. These findings are in keeping with several early experiments demonstrating that manipulations intended to focus attention on the pursuit target improve pursuit performance [Shagass, 1976; Sweeney, Clementz et al, 1994] and that dual task conditions can lead to impairments in at least some indices of pursuit performance (Acker and Toone, 1978; Brezinova and Kendell, 1977;Lipton, Frost et al., 1980). Together these results suggest that attention may play an important role in the maintenance of smooth pursuit eye movements, and support recent research suggesting that the functional organisation of the pursuit system may be more similar to that of the saccadic system than has generally been assumed (Krauzlis, 2004).

Our results are contrary to two recent experiments that found that secondary tasks could, in some circumstances, lead to improvements in smooth pursuit (Van Gelder, Lebedev, Liu, and Tsui, 1995; Kathmann, Hochrein et al., 1999). These findings were used to support the argument that smooth pursuit is a relatively automatic process, one that may in fact operate most efficiently in the absence of any additional attentional control. The reason for the discrepancy between the findings of the present study and these earlier papers is not clear, but an important difference between the studies concerns the nature of the secondary tasks used.

The Kathmann et al study employed two different secondary tasks. The "oddball" task required participants to attend to a sequence of low pitch tones and respond to infrequent ($p = 0.2$) high pitch tones with a key press. It is possible that this simple task made very few demands on the attentional resources involved in pursuit maintenance, an argument supported by the observation that very few errors were made. The "two dimensional discrimination task" was intended to be more difficult and required participants to respond to "long" tones, of either high or low pitch, which occurred infrequently against a background of high or low pitch short duration tones. However, although the task involved stimuli that varied on two dimensions (tone and pitch), participants were only required to respond to one dimension (tone length) again suggesting the possibility that this task made comparatively little demand on attentional resources. It is possible that secondary tasks that make considerably greater demands on attentional resources impair pursuit performance, whereas relatively undemanding secondary tasks have no effect, or may even improve pursuit. However, it should be noted that whilst neither of the “easy” dual task manipulations used in experiment 2 of this study led to impairments in pursuit performance, they did not result in improvements either. Further research is required to determine the particular circumstances in which secondary task performance leads to improvements in pursuit function.

The exact role played by attention in the maintenance of pursuit remains unclear, but one possibility is that it facilitates motion processing. Lesions to the medial superior temporal (MST) and middle temporal (MT) areas lead to severe pursuit deficits in human and non-human primates (Heide, Kurzidim et al., 1996; Dursteler and Wurtz, 1988). Electrophysiological and functional neuroimaging studies have demonstrated that neurons in the medial superior temporal (MST) and middle temporal (MT) areas increase their activity during motion perception (Zeki, Watson et al., 1991) and smooth pursuit eye movements (Komatsu and Wurtz, 1988; Petit and Haxby, 1999). Importantly, recent research has found that the response of these neurons is modulated by attention (Seidemann and Newsome, 1999; O'Craven, Rosen et al., 1997). The suggestion that attentionaly mediated deficits in motion processing may lead to pursuit impairments is supported by research in patients with schizophrenia. Schizophrenia is associated with severe impairments in smooth pursuit (Hutton and Kennard, 1998) and research suggests that these impairments may be linked to impairments in motion processing (Chen, Nakayama et al., 2003;Chen, Levy et al., 1999;Stuve, Friedman et al., 1997). Attentional deficits are well documented in schizophrenia (see e.g. Braff, 1993), and nicotine, which facilitates attentional processing in humans (Rezvani and Levin, 2001) has been shown to improve pursuit performance in these patients by reducing the number of leading saccades (Avila, Sherr et al., 2003; Olincy, Johnson et al., 2003).

It was predicted that spatial attention might be particularly relevant for smooth pursuit, and that secondary tasks that made specific demands on spatial attention would be more likely to impair pursuit performance. This hypothesis was not supported in Experiment 1. One possible reason for our failure to observe differential effects of the two tasks in this experiment is that the spatial distractor task did not make sufficient demands on spatial attention. The tones were presented through headphones, and although this leads to a perception of the tones being located either on the left, right or centrally it is possible that this perception was not sufficiently compelling. Using externally located sound sources with a wider range of possible locations may have led to greater demands being made on spatial attention.

Some support for a role of spatial attention in pursuit was provided in Experiment 2, where tapping a spatially complex pattern led to a comparatively large impairment in pursuit function. The tapping task requires the continual updating of a spatial represention, and it is possible that this overlaps sufficiently with the attentional processing requirements of smooth pursuit to lead to impairments. This observation may have some practical implications. Driving makes considerable demands on the smooth pursuit system – moving objects are tracked in order to determine their position and velocity, and stationary objects are tracked in order to determine their position and the velocity of the vehicle being driven. Numerous studies have found that cell phone use whilst driving leads to considerable reductions in driving performance (e.g. Strayer, Drews et al., 2003). The majority of these studies have focussed on the distracting effects of carrying out a phone conversation whilst driving, but our findings suggest that the act of dialing a number whilst driving may also potentially impair driving ability. Voice activated dialling would be preferential, as neither condition that involved vocalising numbers led to reductions in pursuit performance in Experiment 2.

One limitation of the current study is that the accuracy of secondary task performance was not measured. Therefore it is not possible to determine the extent to which individual participants traded off the tasks against one another. However, informal observations suggested that errors on the secondary tasks in experiment 1 were rare, and the fact that significant reductions in performance were found on three of the four "difficult" dual task conditions suggests that subjects were at least compliant with task instructions.

In conclusion, in this study we found that attentionally demanding tasks led to impairments in smooth pursuit performance, supporting suggestions that attention may play an important role in the maintenance as well as initiation of smooth pursuit eye movements.

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Figure 1a: Means (and Standard Error of the Means - SEMs) of the velocity gain values under different conditions in Experiment 1. Circles = Single Task Control, Triangles = non-spatial secondary task; squares = spatial secondary task.

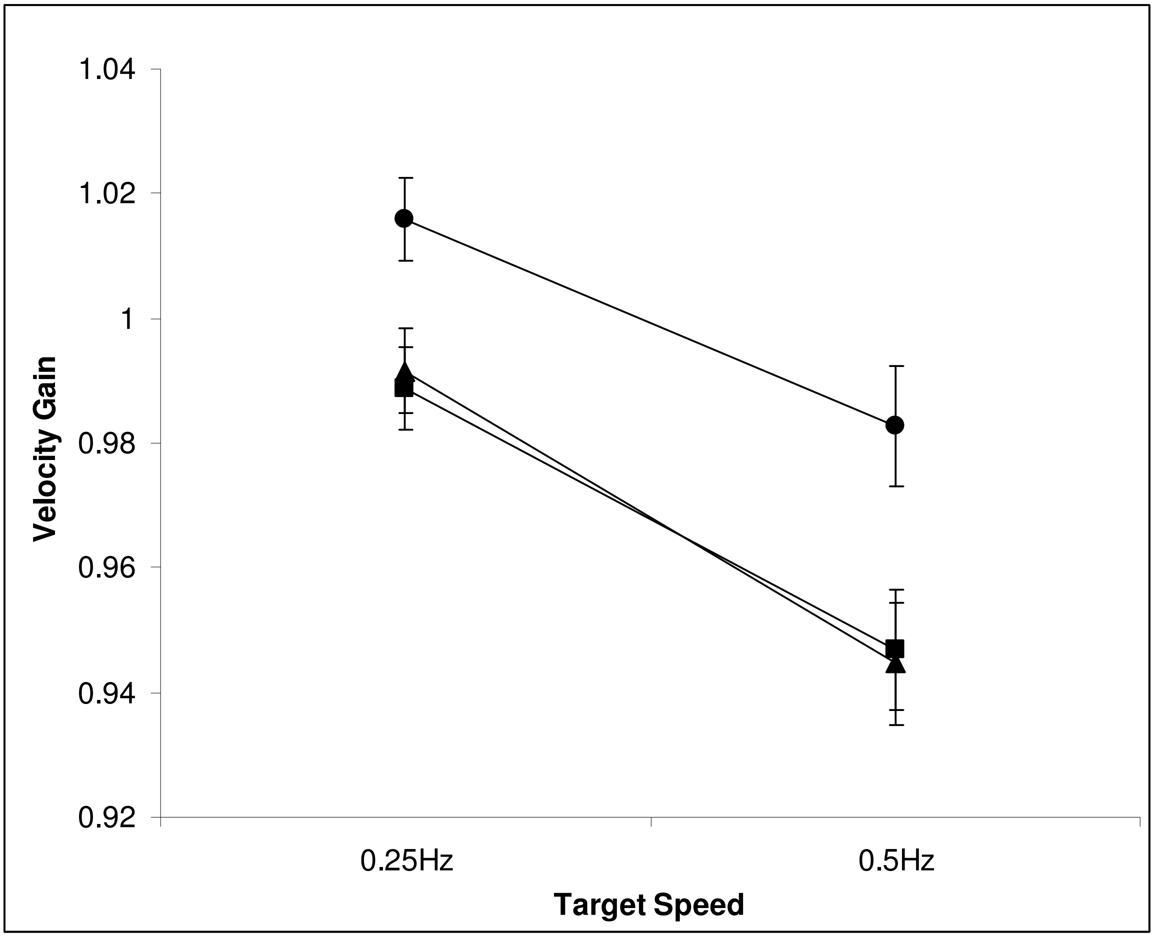


Figure 1b: Means (and SEMs) of the log RMSE under different conditions in Experiment 1. Circles = Single Task Control, Triangles = non-spatial secondary task; squares = spatial secondary task.

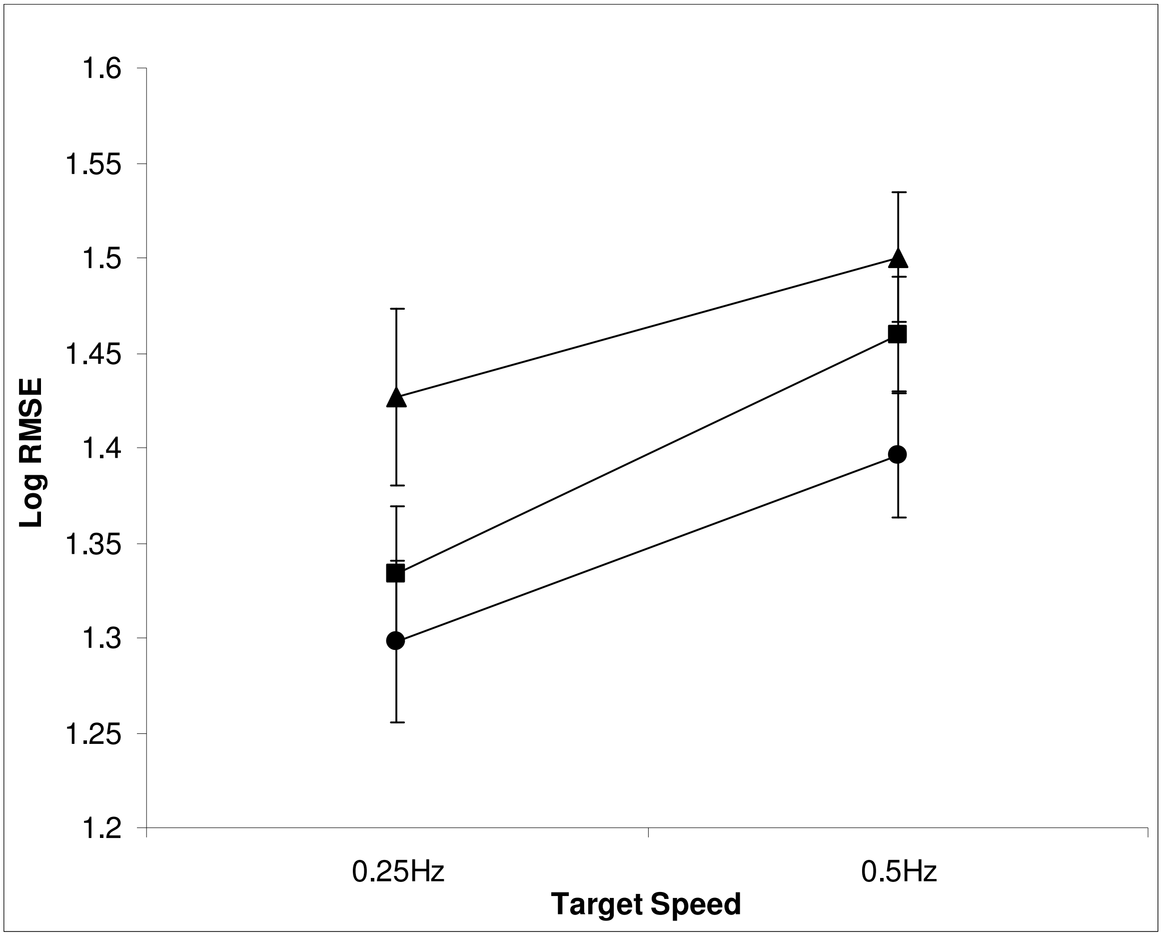


Figure 2a. Means (and SEMs) of the velocity gain values for Experiment 2. Hollow circles = single task control; hollow squares = random number control; filled squares = random number generation; hollow triangle = tapping control; filled triangle = tapping boustrophedon pattern.

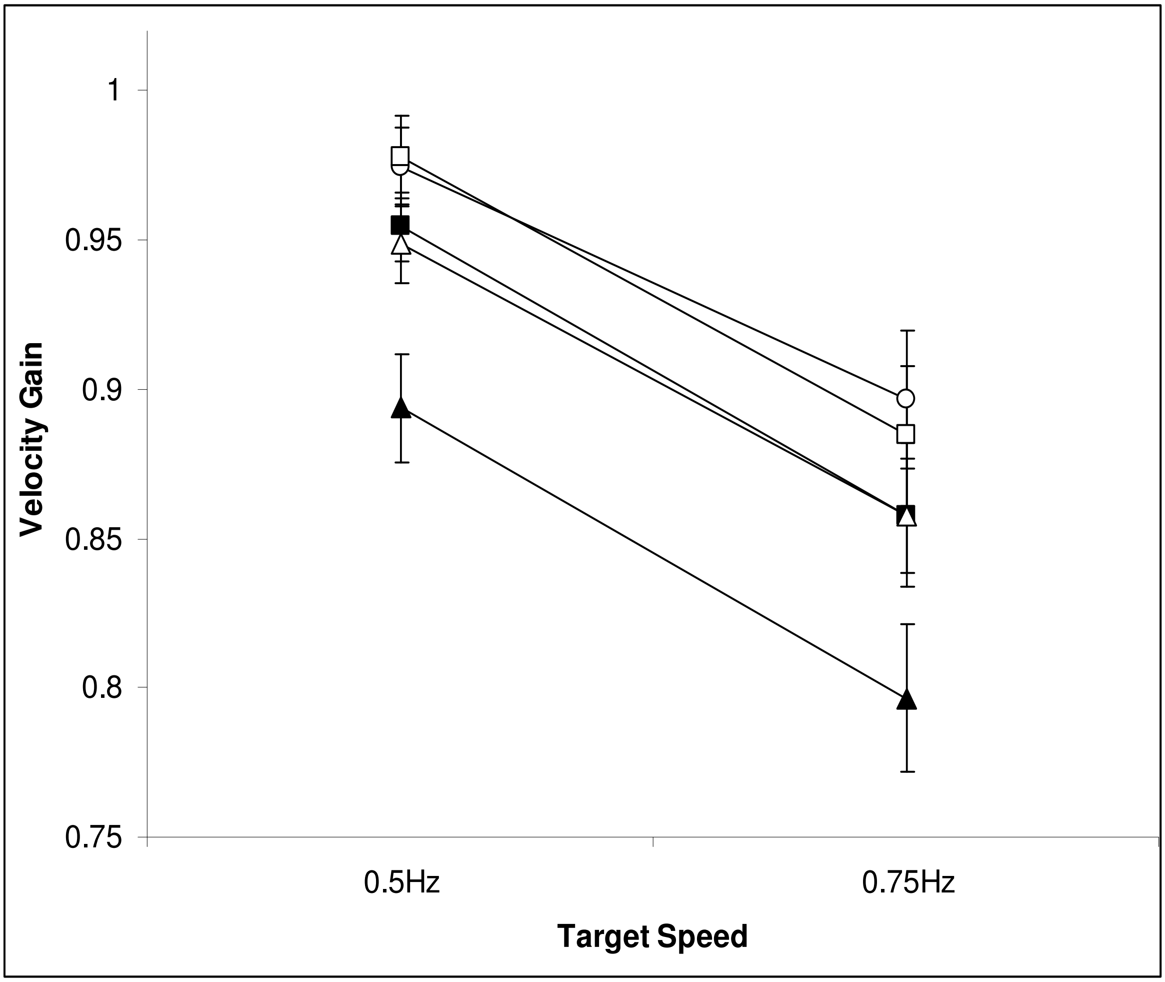
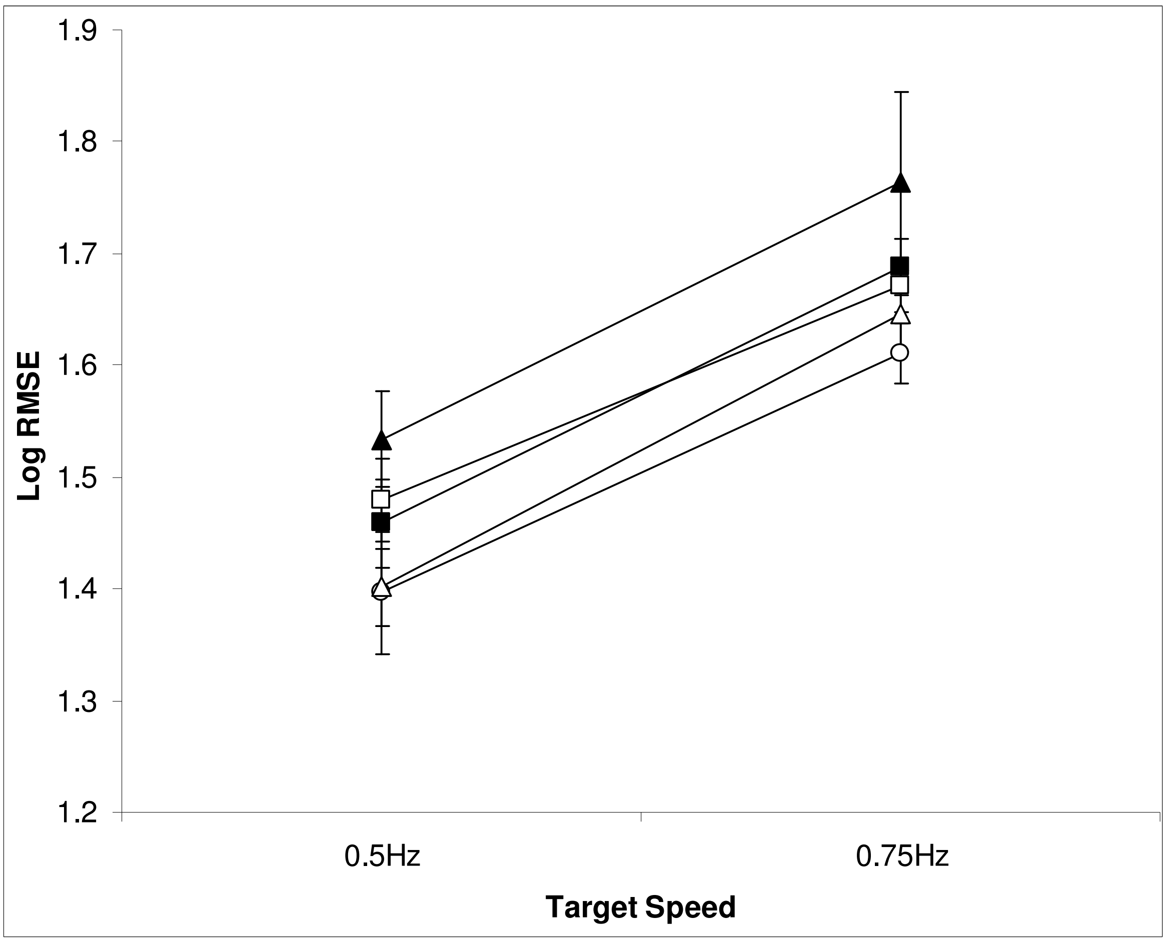


Figure 2b: Means (and SEMs) of the log RMSE values for Experiment 2. Hollow circles = single task control; hollow squares = random number control; filled squares = random number generation; hollow triangle = tapping control; filled triangle = tapping boustrophedon pattern.



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