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Differential Effects of Visual and Auditory Cognitive Tasks on Smooth Pursuit Eye Movements

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ABSTRACT

Smooth pursuit eye movements (SPEM) are important to gather visual information that guides our interactions with moving objects (e.g., tracking a tennis ball, or following a car when driving). In many neurological conditions, from Parkinson's disease to stroke, the voluntary control of SPEM can be compromised. Therefore, SPEMs can serve as sensitive proxies for assessing cognitive and sensorimotor function. Prior research has shown that SPEMs are influenced by attention and working memory load, yet it remains unclear how the sensory modality of concurrent tasks interacts with these effects. Here, we conducted a 3 (working memory load: no load, easy [low load], and hard [high load]) × 2 (sensory modality: visual vs. auditory) experiment to examine how working memory load and secondary task modality interact to affect SPEM in healthy young adults. Participants tracked a moving circle while simultaneously performing an arithmetic task, where they added either constant (1) or variable (1–5) numbers which were presented visually or auditorily. Our results showed that a secondary auditory task increased tracking variability during high cognitive load. In contrast, we found that the visual task improved tracking, reducing variability irrespective of cognitive load. We interpret our results as evidence that auditory processing requires additional top-down control that is critical for the control of smooth pursuit, diverting resources required for smooth pursuit and, consequently, increasing SPEM variability. These findings emphasize the importance of sensory modality in understanding the interactions between working memory and oculomotor control. We suggest that auditory secondary cognitive tasks may provide a more sensitive test of sensorimotor control deficits in future research with clinical populations.

1 | Introduction

Our eyes are in constant motion, playing a fundamental role in perceiving and guiding our interactions with the world around us. Eye movements are controlled by complex neural mechanisms and can be broadly categorized as reflexive—such as the vestibulo-ocular reflex, optokinetic nystagmus, and reflexive saccades—or voluntary, including saccades, smooth pursuit, and vergence movements (Leigh et al. 2015). Voluntary eye movements allow us to focus on and track objects of interest in our environments, shaping our perceptions and actions. These mechanisms, however, can be disrupted in neurological conditions such as Parkinson's disease (Frei 2021), schizophrenia (Brakemeier et al. 2020; Morita et al. 2020), cerebellar ataxia (Salari et al. 2024), mild traumatic brain injury (mTBI; Contreras et al. 2011; Hunfalvay et al. 2021; Stubbs et al. 2019), or stroke (Fracica et al. 2023), where impairments in voluntary movements, including smooth pursuit eye movements (SPEM), compromise visual tracking and functional vision. Importantly, SPEM are also critical for healthy individuals, and investigating when they become disrupted in this population is theoretically relevant for advancing our understanding of sensorimotor and cognitive interactions. In the present study, we focus on the execution of voluntary SPEM, aiming to reconcile apparently discrepant findings in the literature and further our understanding of this key oculomotor behavior.

Early models of SPEM control for single targets conceptualized it as a reflexive or automatic feedback loop, in which the eyes are driven to track a moving target, reducing undesirable "retinal slip" (Lisberger et al. 1987). At first glance, this model suggested that SPEM control might remain largely unaffected by the availability of attentional resources, because all that is required is a voluntary drive to track the object, with the details of movement execution handled by lower-level mechanisms that could act relatively independently of attention. However, Hutton and Tegally (2005) demonstrated that SPEM depends on the availability of attentional resources. More specifically, they showed that directing attention toward the tracked object leads to more stable and consistent pursuit, whereas concurrent tasks demanding internal mental estimations (e.g., arithmetic tasks such as adding numbers) or working memory capacity may disrupt tracking or lead to compensatory increases in catch-up saccades. Therefore, the engagement of attention toward a target and the deployment of neural resources for other tasks can impact the effective control of SPEM.

Despite evidence that attentional requirements modulate SPEM performance, the precise mechanisms by which attention and working memory influence pursuit, and whether these mechanisms are similar across different task domains, remain unclear. In particular, two studies have reported conflicting results. Contreras et al. (2011) found that an increased cognitive load impaired smooth pursuit during a word-recall task in individuals with mild traumatic brain injury but not in healthy controls. In contrast, Stubbs et al. (2018) observed that an increased working memory load during pursuit actually reduced pursuit variability, resulting in more consistent tracking in healthy individuals, with changes that were specific to attentional focus. Therefore, the effects of cognitive demand on SPEM performance and whether any interference is modality-specific remain important research questions. In the present study, we aimed to examine how varying levels of working memory load (easy vs hard) and secondary task modality (visual vs auditory) could affect smooth pursuit eye movements in healthy young adults.

Drawing from the conflicting results obtained by Contreras et al. (2011) and Stubbs et al. (2018), we derived directional hypotheses regarding the effects of cognitive load on SPEM. We predicted that under minimal cognitive load, SPEM would remain largely unaffected relative to control conditions. In contrast, when the cognitive demands were increased by incorporating random numbers into the arithmetic task, we predicted that the modality of task presentation would have differential effects on SPEM. More precisely, we predicted that while visually presented random numbers would reduce SPEM variability, the same cognitive challenge delivered auditorily would increase variability. We interpret our outcomes in light of recent evidence on the frontal cortex's role in actively controlling working memory (Shao et al. 2024), as well as the activation of the primary visual cortex during spoken language processing (Seydell-Greenwald et al. 2023).

2 | Method

2.1 | Participants

Thirty-five young, healthy adults (21 female) with an age bracket ranging from 18 to 29 years old (Mean: 21.43, SD: 2.86) volunteered to participate in this study in exchange for course credit. All participants were recruited from the undergraduate psychology program at Curtin School of Population Health. Participants reported normal or corrected-to-normal vision with no known history of neurological conditions affecting eyesight. This study was approved by the Curtin Human Research Ethics Committee (HRE2018-0257) and all participants gave written informed consent before participating. Due to the conflicting effect sizes reported by Contreras et al. (2011) [12 control participants] and Stubbs et al. (2018) [15 participants], and because our study employed different cognitive tasks, a formal power analysis was not deemed reliable. Instead, we selected a sample size informed by previous research and adopted a conservative approach by recruiting more than twice the number of participants used in those studies.

2.2 | Procedure

At the beginning of the experiment, the eye-tracker was calibrated using a nine-point calibration procedure. Drift corrections were performed after each trial, before the stimulus target started moving on screen. During the experiment, participants placed their chin on a rest positioned 57 cm from the monitor screen. Participants were required to track a moving circle displayed on the monitor screen and add numbers that were presented either verbally or shown embedded within the moving target (see Figure 1).

2.3 | Instruments and Apparatus

Visual stimuli were displayed on a BenQ XL2420TE computer monitor (24-in) with a 1920 × 1080 resolution operating at 60 Hz. Auditory stimuli were delivered via headphones (Corsair, HS55 Stereo) throughout the experiment. The experiment was programmed and run using MATLAB 2015b and PsychToolbox extensions (Brainard 1997; Kleiner et al. 2007). Eye position was recorded using an EyeLink 1000 Plus (SR Research, Ontario, Canada), sampling at a rate of 1000 Hz. Data from the right eye were analyzed.

2.4 | Stimuli and Task

The primary task involved a smooth pursuit eye movement in which participants tracked a black circle (subtending 1.8° of visual angle) on a gray background (see Figure 1). The pursuit target moved along a circular trajectory with a radius of 9.2° of visual angle, with a period of 2.5 s (0.4 Hz), resulting in a constant tangential velocity of 26°/s, following Stubbs et al. (2018). The circular trajectory was presented within the boundaries of the monitor screen and covered 360°. The direction of the pursuit target's motion (clockwise or counterclockwise) was randomly assigned on a trial-by-trial basis.

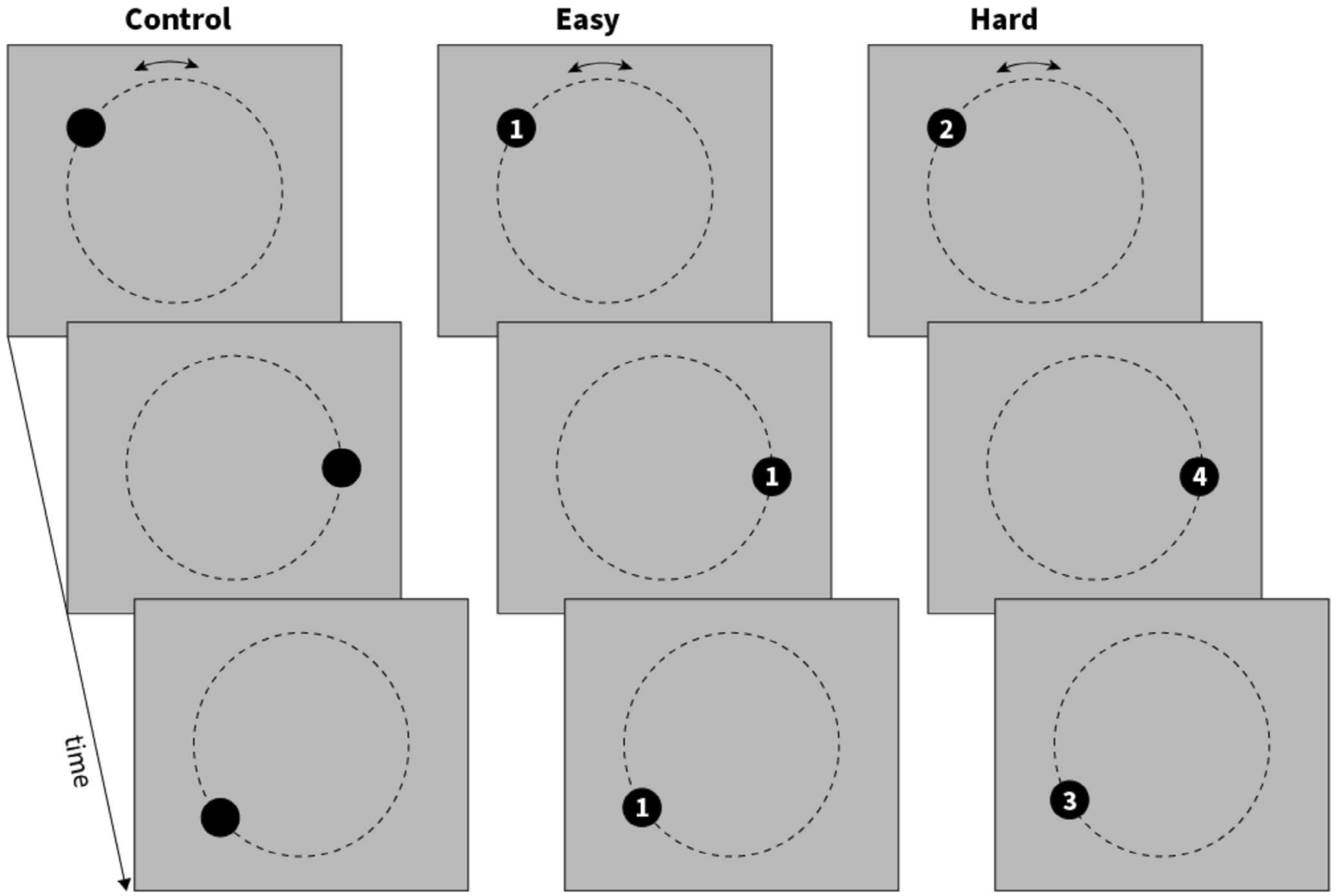

FIGURE 1 | Illustration of the smooth pursuit eye movement task under three experimental conditions: Control, Easy, and Hard. Each condition required participants to track a black circle moving along a circular trajectory on a gray background at a constant speed. In the Control condition (Left), no concurrent arithmetic task was presented. In the Easy condition (Middle), participants performed a simple arithmetic task by adding the number one to the previously presented number (e.g., $1+1=2$). In the Hard condition (Right), participants added random numbers from 1 to 5 to the previously presented number (e.g., $3+2=5$). Numbers were presented either visually within the pursuit target or auditorily through headphones, with identical onset times and a duration of 500 ms for each presentation. The dashed line represents the trajectory of the moving circle, which was not visible to participants.

In addition to the tracking task, participants performed a concurrent arithmetic task with two levels of difficulty (easy and hard), with numbers presented either visually or auditorily. The numbers had a height of 0.6° of visual angle and were displayed every 1.5 s, resulting in a total of 17 numbers per pursuit trial. The first number in the sequence appeared 5 s after the onset of the pursuit target's motion. In the easy condition, participants added one to the previous number they saw or heard (e.g., adding to $1=2$; adding to $2=3$, etc.) as shown in Figure 1 (middle). In the hard condition, participants added a randomly chosen number between 1 and 5 to the previously presented number, updating the running total (Figure 1, right). In the auditory condition, numbers were delivered through headphones, whereas in the visual condition, they were presented within the central disc of the moving pursuit target. In both modalities, each number was presented for 500 ms. Auditory stimuli had a peak intensity of approximately 65 dB(A) and were temporally adjusted using Audacity software to ensure presentation duration matched that of the visual condition. A control condition, in which no numbers were presented, was also included.

Each trial began with the black target, initially positioned at 270°, to the left of the screen on the horizontal meridian. At the beginning of every trial, a drift correction was presented at the initial position of the moving target, after which the target began its motion. Before the drift correction adjustment, participants were informed about the difficulty level of the task (Control, Easy or Hard) as well as the modality of presentation of the stimuli for the arithmetic task (Visual or Auditory). The pursuit task lasted approximately 30 s, and the trial ended with the disappearance of the stimulus. Participants were then asked to verbally provide their answer to the sum of all numbers, which was inputted by the experimenter using the keyboard of the experimental computer.

Each participant completed a total of 18 trials, 3 for each combination of modality (visual, auditory, or control) and difficulty (easy, or hard). The trials in the control condition consisted of a disc moving clockwise or counterclockwise on the monitor screen, but no visual or auditory numbers were presented. The allocation of control trials, which served as a comparison for the auditory or visual condition, was pseudo-randomized. Therefore, we predicted no differences between control trials. The task was thoroughly explained to participants before the beginning of the trials. No practice trials were performed. In a preliminary analysis, we found that removing the first trial in each condition yielded results that were highly similar to those using all data. Consequently, all trials were retained for analysis.

2.5 | Data Processing and Analysis

Files were transformed from the EyeLink default format (EDF) to the ASC format and loaded into R using the 'read.asc' function from the 'eyelinker' package. Eye position metrics were extracted from the whole trial period after the moving target started its motion. Initial processing of the data removed blinks identified by the EyeLink 1000 Plus algorithm. Subsequently, we also visually inspected all trials and removed any changes in XY coordinates that resembled a blink that could have been missed by the eye tracker's algorithm. We excluded trials where participants could not track the moving target. While we monitored for excessive and long blinks, as well as excessive saccades or prolonged stationary gaze, in practice, exclusions were based only on trials where the eye tracker provided poor quality data that did not reflect the expected sinusoidal pattern of XY coordinates required for the tracking task. Specifically, we excluded trials due to excessive blinks where the sinusoidal pattern was not clear. A chi-square test showed that the distribution of discarded trials differed significantly by condition ($\chi^2=7.09$, $p=0.029$): 6 of the 8 excluded trials came from the Hard condition, while none came from the Easy condition. Additionally, we removed the first 2 s of data of each trial to make sure participants were engaged in the tracking task. Different from previous studies (Contreras et al. 2011; Stubbs et al. 2018), we refrained from removing saccades from our smooth pursuit data before the two-dimensional analysis. While we acknowledge that saccades could be considered noise and not reflective of pure smooth pursuit behavior, we chose not to remove these, as they can be considered part of the overall pursuit strategy, and their control could inform our understanding of the overall oculomotor response to our task demands. In fact, current understanding in the field suggests that saccades and pursuit are two behavioral outputs stemming from a single sensorimotor process (Goettker and Gegenfurtner 2021; Orban de Xivry and Lefevre 2007). Consequently, all analyses were conducted on time series where both pursuit and potential saccadic components were present. In total, only 1.27% of trials were discarded (8 out of 630 trials).

In our analysis of eye movements, we chose to focus on the consistency of the gaze trajectory rather than on an absolute phase alignment between the eye and the target. Stubbs et al. (2018) incorporated phase shift to quantify pursuit variability, correcting for the timing offset between eye and target positions. However, their simpler calculation of radial variability produced the same basic pattern of results as measures incorporating phase shift errors. Moreover, tangential errors that account for phase shift might be overinflated by blinks. For example, if participants blink more often in one condition, tangential errors may increase because participants may resume tracking at an incorrect position and need time to catch up with the moving target, resulting in transient errors that disproportionately inflate tangential variability. These transient errors may be more indicative of the lack of visual input during blinks rather than deficiencies in eye movement control.

Our emphasis, therefore, was on the consistency of the pursuit pattern over time, as we aimed to measure how consistently the gaze maintained radial distance when tracking the moving target. We quantified the radial standard deviation, independently of angular errors, which allowed us to capture the stability of the eye movement without being influenced by minor phase offsets or small catch-up saccades. In addition, we considered the percentage of data points removed due to blinks within trials as a secondary measure of task difficulty, given prior research showing a relationship between eye blinks and cognitive load (Magliacano et al. 2020; Siegle et al. 2008).

To examine how task difficulty and stimulus modality influenced radial variability, we used Linear Mixed Models (LMMs) and Bayesian LMMs. These models included participant ID as the random factor and Task Difficulty and Stimulus Modality as the fixed factors. We also entered the percentage of blinks removed as a continuous covariate in the model to control for the possible effects of blinks on radial variability. The models were run using the 'lme4' (Bates et al. 2009) and 'brms' (Bürkner 2017) R packages. All models converged, and random effects and residuals of the frequentist model showed acceptable normality as assessed using the 'performance' package (Lüdecke et al. 2021). Type III Wald Chi-squared omnibus tests for the frequentist models were obtained using the Anova function from the car package (Fox et al. 2012). We provide semi-partial R^2 and their 95% CIs as a measure of effect size. The Bayesian models included default, non-informative priors and incorporated a Student's t-distribution for robustness. Sampling was conducted with four chains, each with 5000 iterations. Additionally, we compared Bayesian models with specific combinations of predictors to assess the contribution of Task Difficulty, Stimulus Modality, and their interaction to radial variability. For these comparisons, the percentage of blinks removed was retained as a covariate in all models to control for its potential effects. Using Bayes factors, we quantified the strength of evidence for including each term (Task Difficulty, Stimulus Modality, or their interaction) by comparing models with and without these terms. A Bayes factor greater than 1 indicates support for the more complex model (e.g., including the interaction term), with larger values representing stronger evidence (see Raftery 1995).

3 | Results

The frequentist LMM revealed a significant main effect of Task Difficulty on radial variability, $\chi^2=59.72$, $p<0.0001$. However, the effect of Stimulus Modality failed to reach statistical significance, $\chi^2=0.023$, $p=0.88$, suggesting that modality alone did not significantly affect SPEM radial variability. The interaction between Task Difficulty and Stimulus Modality was statistically reliable, $\chi^2=40.97$, $p<0.0001$, indicating that the effect of task difficulty on radial variability depends on the sensory modality in which the numbers were presented. Visual inspection of the interaction plot (see Figures 2 and 3) shows that, in the Hard condition, radial variability was greater in the auditory modality compared to the visual modality, whereas this difference was less pronounced or absent in the Control and Easy conditions. The covariate, percentage of blink-related removed data points, revealed a statistically significant effect, $\chi^2=29.95$, $p<0.0001$, demonstrating that the higher the percentage of blink-related removed data points, the higher the radial variability in SPEM. This highlights the importance of controlling for eye blinks in our main analysis. The fixed effects in the model explained approximately 19.4% of the variance in radial variability (95% CI [14.6%, 26.3%]), representing a medium-to-large effect size (Nakagawa and Schielzeth 2013). Table 1 shows the estimates of the fixed effects from this frequentist model.

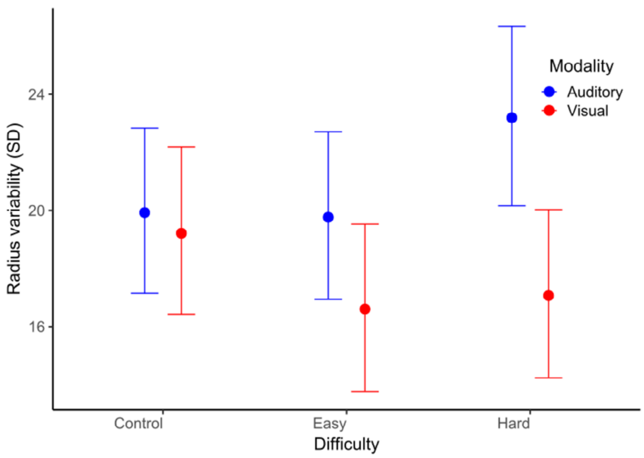

FIGURE 2 | Interaction effects of task difficulty (control, easy, and hard) and modality (auditory and visual) on radial variability (SD), modeled using a robust Bayesian LMM. Control trials, which lacked number presentation in either modality, were randomly allocated as controls for each modality (3 control trials each, 6 total). The plot shows model-estimated means with 95% credible intervals for each combination of difficulty and modality.

While we controlled for the percentage of blink-related removed data points in our main analysis, we also conducted a follow-up analysis to test the robustness of our results using a more stringent trial inclusion criterion. More specifically, we removed from the analysis any trials in which blink-related data loss was equal to or greater than 10%. This additional analysis confirmed the main effects and interactions were unaltered: Task Difficulty, $\chi^2 = 45.77$, $p < 0.0001$; Stimulus Modality, $\chi^2 = 0.10$, $p = 0.74$; Interaction, $\chi^2 = 49.90$, $p < 0.0001$; Covariate (percentage of blinks removed), $\chi^2 = 13.47$, $p = 0.0002$.

Following a suggestion from one of our reviewers, we included trial number as a covariate in the main model. This variable can be informative in detecting potential practice or fatigue-related effects that might influence the interpretation of our results. The additional analysis corroborated our original findings and revealed no significant effect of trial number on radial variability ($\chi^2 = 0.44$, $p = 0.51$).

Bayesian model comparison using Bayes factors revealed decisive evidence for including Task Difficulty ($BF = 7.3 \times 10^{17}$), Stimulus Modality ($BF = 3.1 \times 10^{35}$), and their interaction ($BF = 3.5 \times 10^{11}$) in the model. These results corroborate the frequentist analysis and confirm the importance of the interaction between task difficulty and stimulus modality in explaining radial variability in SPEM tasks.

As changes in SPEM variability could be linked to changes in performance (e.g., participants performing at different levels between conditions), we also analyzed whether there were any systematic changes in the secondary addition task that could explain

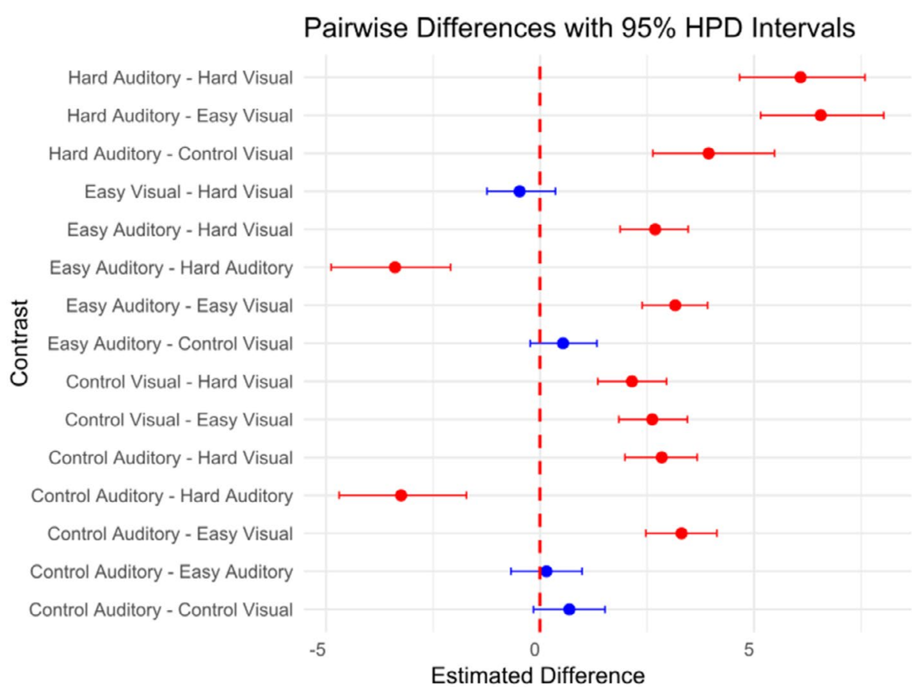

FIGURE 3 | Pairwise differences in radial variability for the interaction of task difficulty (Control, Easy, Hard) and modality (Auditory, Visual), estimated using a robust Bayesian LMM, and extracted using the emmeans package (Lenth et al. 2018). Each point represents the estimated difference for a given contrast, with error bars indicating the 95% highest posterior density (HPD) intervals. Contrasts where the credible interval does not include zero (dashed red line) are highlighted in red, indicating significant differences. Contrasts where the credible interval crosses zero are highlighted in blue, indicating no evidence for significant differences.

TABLE 1 | Estimates of the fixed effects (individual factor-level contrasts against reference category) from the frequentist LMM, including standard errors and Wald t tests.

Term	Estimate	Std. error	Statistic	p value
Difficulty easy	−0.201	1.553	−0.129	0.897
Difficulty hard	10.74	1.612	6.661	0.000
Modality visual	0.234	1.556	0.150	0.880
Difficulty easy × modality visual	−4.756	2.205	−2.157	0.031
Difficulty hard × modality visual	−14.079	2.238	−6.290	0.000
Removed blink% (continuous variable)	4.316	0.788	5.473	0.000

our results. A LMM on the error calculations (sum of all numbers presented—the answer participants gave) was conducted. The results showed no effect of Stimulus Modality, $\chi^2 = 0.087$, $p = 0.76$, nor interaction between Task Difficulty and Stimulus Modality, $\chi^2 = 0.975$, $p = 0.32$. There was, however, an effect of Task Difficulty on error calculations, $\chi^2 = 5.126$, $p = 0.023$. This effect was expected because the Easy condition only required participants to remember how many ones were presented, whereas the Hard condition required participants to actively add and hold a running total in working memory throughout the trial. The fixed effects explained only a small proportion of the variance in performance, with a marginal R^2 of 0.040 (95% CI [0.018, 0.086]). Consistent with the frequentist approach, a Bayesian ANOVA to assess the effect of Task Difficulty on error calculations showed strong evidence for including Task Difficulty in the model, with a BF of 154.81 compared to the null model. In contrast, the evidence for Stimulus Modality (BF = 0.13) and the Task Difficulty × Stimulus Modality interaction (BF = 0.18) was against their inclusion in the model, favoring the null model over models that included these terms.

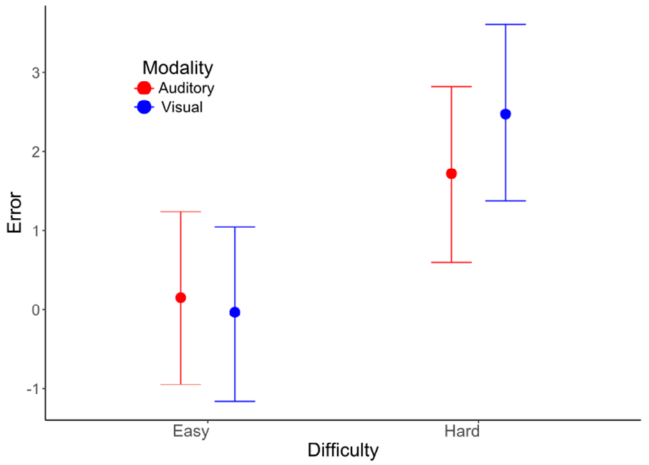

FIGURE 4 | Interaction effects of task difficulty (control, easy, and hard) and modality (auditory and visual) on adding errors, modeled using a robust Bayesian LMM. The plot shows model-estimated means with 95% credible intervals for each combination of difficulty and modality. Note that in the hard condition, the sum of all numbers could range from 17 to 85.

4 | Discussion

The primary goal of the present study was to examine how varying working memory load and the modality of the presentation of numbers in a secondary arithmetic task would affect SPEM movements in healthy young adults. Previous work by Contreras et al. (2011) demonstrated that the auditory presentation of words during SPEM increased movement variability. In contrast, Stubbs et al. (2018) reported a decrease in SPEM variability when the secondary task, an n-back task, involved visual stimuli. These findings suggest that increased cognitive load—whether via an n-back task or a list of words to be remembered—affects SPEM variability differently depending on the secondary task modality. However, differences in the tasks and modalities across studies may have contributed to these conflicting results. In addition, Contreras et al. (2011) found that the word list task affected SPEM variability only in mTBI patients, not healthy participants, whereas Stubbs et al. (2018) observed significant effects of the n-back task in healthy participants. To address these inconsistencies, we designed a secondary arithmetic task with two levels of difficulty (easy: add 1 vs. hard: add random numbers from 1 to 5) that systematically varied the modality of number stimuli (visual or auditory) to better understand these interactions.

As a first step, we sought to verify that our manipulation of cognitive load successfully affected task difficulty by examining performance on the secondary task. Indeed, participants were less accurate in their calculations in the Hard condition compared to the Easy condition (Figure 4). Importantly, despite this difference in difficulty, there were no differences between visual and auditory modalities in either the Easy or Hard conditions. Therefore, performance on the secondary task was similar across modalities for both cognitive load levels. While this similarity alone does not rule out task prioritization, follow-up analyses examining trial-by-trial performance revealed no significant correlation between arithmetic error and tracking variability (LMM: all $p > 0.43$ for error main effect and interactions; Bayesian LMM: 95% CI for the main effect of error included zero [Estimated. = −0.22, 95% CI: −1.61 to 1.15], as did CIs for all interactions involving error), providing no direct evidence for a performance trade-off. This suggests the observed differences in tracking variability more likely result from modality-specific processing demands rather than a simple shift in task prioritization.

4.1 | Effects of Processing Load

In relation to control trials, it is clear from Figures 2 and 3 that introducing an easy arithmetic task in the visual domain—tracking how many ones were presented—reduced radial tracking variability. While this Easy condition was intended to provide a low-cognitive-load comparison that included sensory input, the observed reduction in eye movement variability raises further questions. It is possible that the mere presence of the visual number stimulus, by providing a more focal point for tracking, contributed to the reduced variability, potentially independent of the minimal arithmetic load. An additional control condition involving stimuli to be ignored could clarify this sensory/attentional component. The results were similar when the Arithmetic task was hard—adding random numbers from 1 to 5. Although there was a clear difference in terms of performance between hard and easy conditions as shown in Figure 4, there was no further reduction in radial tracking variability associated with an increase in task difficulty. These results are largely consistent with those reported by Stubbs et al. (2018) using an n-back task where they reported a reduction in smooth pursuit variability when they introduced the secondary task. While Stubbs et al. (2018) noticed a further reduction in variability as the task became harder (1-back to 2-back), we did not find any evidence of a further reduction in pursuit variability as cognitive demand increased. Therefore, our results are not immediately consistent with the proposal that an increase in attentional demands could lead to a reduction in tracking variability. In our study, it seems that the determinant factor to observe a reduction in tracking variability was the requirement to pay attention to the numbers presented on the moving target, not the level of cognitive demand of the task. Of course, while our results are consistent with Stubbs et al. (2018) regarding the direction of the effects, the fact that no further improvement occurred in the hard condition might be related to differences in the task requirements or data processing choices.

In relation to the effects of the arithmetic task involving the auditory domain, we observed no change in tracking variability when the secondary task had a low cognitive demand. However, the high cognitive demand condition resulted in an increase in tracking variability. This pattern of results is consistent with what Contreras et al. (2011) found with mTBI participants, but at first glance appears different from what they reported for control participants. For control participants, Contreras and colleagues reported that they improved their pursuit synchronization at an intermediate level of task difficulty (remembering 1-word) but showed no difference in relation to the no-word control condition with an increased cognitive load (remembering 5-words). While our results corroborate those of Contreras et al. (2011) for mTBI participants, our study used participants with no known neurological conditions, similar to their control participants. However, the improved performance of their control participants in the low-load condition followed by a plateau in performance in the high-load condition indicates a negative impact of increased cognitive load, suggesting that the pattern of their controls was not that different from ours. Despite differences in task design and outcome measures, the overall pattern of their results with control participants is consistent with our own, suggesting that a high level of cognitive load impairs pursuit across groups.

An additional consideration regarding Contreras et al.'s (2011) study is that different from our task, their participants heard the words before the tracking task started. While this could affect working memory requirements during the task, we would argue that it is likely that auditory cortex processes were engaged in this instance as demonstrated in imaging studies with humans (Gagnepain et al. 2008; Kumar et al. 2016) and electrophysiological recordings in animals (Yu et al. 2021). Therefore, while the delivery of stimuli in our study and that of Contreras et al. (2011) diverged, it is likely that both studies involved sound representations in the auditory cortex. The main difference is that our task required participants to manipulate the presented auditory information in real time through mental arithmetic calculations, particularly during hard condition, whereas Contreras et al. (2011) only required the rehearsal of the information in working memory. In that sense, it could be argued that our task may have been more effective to challenge even control participants with no known neurological impairments, leading to clear impairment in eye movement control.

Altogether, our results are broadly consistent with those reported by both Stubbs et al. (2018) and Contreras et al. (2011). More specifically, we showed that an increase in cognitive load can have divergent effects on eye tracking motor control when the information for the secondary cognitive task (numbers) is presented via auditory or visual sensory channels. However, we did not find evidence that additional attentional demands when the stimuli were presented visually led to an additional reduction in tracking variability. This may be attributed to differences in the cognitive tasks, a flooring effect, or related to our data processing approach. More interestingly, however, is to discuss the reason as to why stimuli presented auditorily and visually might result in opposite effects on tracking variability. We discuss possible mechanisms that could lead to differing results next.

4.2 | Neurophysiological Mechanisms

While our auditory task may have primarily engaged auditory representations, it does not preclude involvement of the auditory cortex when numbers were presented visually. It is well established that visually presented stimuli are often rehearsed sub-vocally to improve retention, and that articulatory suppression—a reduction in the ability to retain information in working memory when engaging in verbal tasks—can impair performance (Baddeley et al. 1984). Articulatory suppression can impair digit span working memory even when the numbers are presented and must be remembered in sign language (Liu et al. 2016). Therefore, it could be argued that both arithmetic tasks in our study required the engagement of the auditory cortex irrespective of the modality of presentation of the stimuli. It is, thus, intriguing that tasks with a theoretically equal level of difficulty, where participants performed at a similar level, would result in opposite effects on eye movement variability during tracking.

While there is ample evidence that visual stimuli (numbers) can be repeated sub-vocally in our brains (Baddeley et al. 1984; Liu et al. 2016), less widely known is the fact that meaningful auditory stimuli may similarly activate the primary visual cortex. This activation is well documented in blind individuals when they hear language stimuli (Bedny et al. 2011; Burton et al. 2002; Roder et al. 2002) but has been recently observed in sighted individuals as well (Seydell-Greenwald et al. 2023). If that is the case in our study, auditory and visual stimuli in our task might both be activating respective sensory cortices. Assuming this is a possibility, why would we have observed opposite effects when the arithmetic task was presented auditorily versus visually? One possibility is that the visual presentation of the numbers forces participants to be more accurate in the task so that they can clearly differentiate numbers and perform the estimation internally. Although this explains why they would be more consistent in the visual condition, it does not explain the increased variability in the auditory version of the task. We speculate that since numbers can be read internally in an automatic fashion with minimal cognitive effort (Keha et al. 2024), visually presented numbers place fewer demands on our cognitive resources, resulting in more consistent pursuit. In contrast, while numbers presented acoustically can also activate the visual cortex, this requires greater cognitive effort diverted to creating a visual representation of the number, akin to visual imagery, which interferes with effective smooth pursuit. This possible interference from internally generated visual representations is supported by recent findings reported by Korda et al. (2023), who demonstrated that an internal task explicitly requiring visuospatial processing resulted in greater variability in SPEM than an arithmetic task. They interpreted this result as increased competition for shared visuospatial attentional resources, an idea consistent with our hypothesis that recruiting visual resources via imagery during the auditory task may underlie the increased SPEM variability we observed.

Also consistent with this crossmodal interference interpretation, a recent study by Gurtner et al. (2021) on mental imagery showed that while the spatial patterns of eye fixations during visual imagery resemble those observed during perception, the temporal patterns of gaze behavior are unique to mental imagery, and that they are further influenced by the semantic content of the imagined stimulus. They argued that these spatial and temporal idiosyncrasies take place because of ongoing processes in charge of generating, maintaining, and protecting mental images from interference (Gurtner et al. 2021). This proposal aligns well with our hypothesis that a more effortful process is required to generate and maintain a visual representation based on auditory information, as compared to directly processing visual numbers, and that this process interferes with smooth pursuit, leading to a more variable tracking performance.

Further evidence supporting our hypothesis comes from a recent functional magnetic resonance imaging study investigating interactions between prefrontal and visual cortices during working memory. More specifically, Shao et al. (2024) found that the maintenance of visual imagery in the visual cortex depends on activity in the prefrontal cortex, particularly during working memory tasks that require active control of mental representations. Consistent with their findings, we propose that the structure of our auditory arithmetic task might have increased the need for this active control over the to-be-remembered numbers, creating a competition with the resources used for smooth pursuit and leading to increased tracking variability. In contrast, the more direct access of the visual stimuli to the visual cortex might have minimized the need for such higher-level control, allowing more resources to be allocated to smooth pursuit, which in turn would allow for less variability in tracking.

Future studies using fMRI, similar to investigations of functional connectivity during SPEM (Schröder et al. 2020), could more directly investigate whether auditory working memory tasks coactivate prefrontal regions involved in oculomotor control more strongly than visual tasks under high load. Such studies could also examine whether the degree of activation overlap or task-dependent functional connectivity between working memory and oculomotor networks could predict smooth pursuit disruption.

5 | Conclusion and Broader Implications

We have replicated and extended seemingly conflicting findings in the literature on smooth pursuit eye tracking. Increased cognitive load disrupted smooth pursuit when the secondary task was auditory. We interpret this finding as evidence of a competition between the generation and maintenance processes, akin to mental imagery when no visual input is provided, therefore taking away resources from the prefrontal cortex that are important for smooth pursuit control (Chen et al. 2002). We found that a secondary visual demand led to an enhancement of SPEM by attracting attention to the moving target, and there was no evidence that a more difficult visual task impaired performance. These findings demonstrate the importance of sensory modality in mediating the effects of cognitive load on SPEM performance. We believe our task manipulations (auditory vs. visual, easy vs. hard) offer a path to better understand the interactions between attention, working memory, and oculomotor control in future research.

Given that smooth-pursuit eye movements have been associated with several neurological conditions and brain injuries (Brakemeier et al. 2020; Contreras et al. 2011; Fracica et al. 2023; Frei 2021; Hunfalvay et al. 2021; Morita et al. 2020; Salari et al. 2024; Stubbs et al. 2019), it seems appropriate to discuss the implications of our study for further research on clinical applications. Our findings suggest that the sensory modality of the secondary cognitive task has a substantial impact on smooth pursuit performance. More specifically, a secondary auditory task places a greater burden on cognitive resources, resulting in more challenging eye movement control and, consequently, higher tracking variability. Our findings suggest that an auditory task with higher cognitive load engages prefrontal cortex resources, which is relevant for clinical populations known for having impairments of the frontal cortex, such as individuals with mild traumatic brain injury, stroke, or neurodegenerative diseases.

While we tested only healthy young adults, our data indicates that our task was challenging enough to push participants to use their cognitive resources to the point of compromising eye movement control. Given that both aging and neurological conditions are known for impacting cognitive resources, our findings suggest that smooth pursuit assessment coupled with a cognitively demanding auditory task might be useful for revealing more subtle impairments in these populations, that would otherwise remain undetected by tasks involving similar difficulty but with visual or visuospatial properties. Future research should consider that a more sensitive and specific diagnostic investigation would require a more detailed study including a wider range of cognitive loads and measures. This would help to fully capture a potential inverted-U pattern of SPEM performance that was shown to exist for control participants in Contreras et al.'s (2011) study.

Author Contributions

Geoffrey Kaye: conceptualization, investigation, writing – original draft, methodology, writing – review and editing, formal analysis, project administration, data curation. **Edan Johnston:** formal analysis, writing – original draft, writing – review and editing. **Jaiden Burke:** formal analysis, writing – review and editing, writing – original draft. **Natalie Gasson:** writing – original draft, writing – review and editing, supervision, conceptualization. **Welber Marinovic:** conceptualization, investigation, writing – original draft, methodology, writing – review and editing, software, formal analysis, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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