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Mind over body: Interfering with the inner voice is detrimental to endurance performance

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ABSTRACT

In two preregistered experiments, we investigated whether covert language is involved in sustained physical efforts, specifically if people are less able to push themselves physically when distracted from using inner speech. In both experiments, participants performed 12 cycling trials (Experiment 1: N = 49; Experiment 2: N = 50), each lasting 1 min where participants were required to cycle as fast as possible while simultaneously engaging in either a visuospatial task, a verbal task or no interference. Experiment 1: Participants performed worse in the verbal interference condition compared with the control condition ($d = 0.29$) and verbal interference performance was numerically but not significantly worse than visuospatial interference ($d = 0.22$). Experiment 2: A more demanding interference task yielded significant slower cycling with verbal interference compared to both control ($d = 1$) and visuospatial interference ($d = 0.43$). These results indicate that inner speech plays a causal role in control of sustained physical efforts.

1. Introduction

Language and motor control are usually conceived of as separate cognitive systems with little influence on each other. However, if we consider (prolonged, sustained) motor control as requiring executive functions, then a connection seems plausible, as executive functions have a long, linked history with language (Alderson-Day & Fernyhough, 2015; Cragg & Nation, 2010). Covert language plays a role in cognitive control (Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Tullett & Inzlicht, 2010; G. L. Wallace, McKinlay, et al., 2017), and cognitive control plays an important role in reaching optimal physical performance (Brick, MacIntyre, & Campbell, 2016; Hyland-Monks, Cronin, McNaughton, & Marchant, 2018; Kirschenbaum, 1987; McCormick, Meijen, Anstiss, & Jones, 2019). In the present study, we combine findings from sport psychology with the dual-task interference method designed to test the specific involvement of inner speech in a given task (Nedergaard, Wallentin, & Lupyan, 2022). In sport psychology, self-talk interventions have been found to improve performance while dual-task interference paradigms from cognitive psychology have been used to investigate the role of verbal rehearsal in various cognitive processes. We conducted two experiments testing non-expert participants' cycling performance on an exercise bike under two different interference conditions (verbal and visuospatial) and a no-interference control condition. This extends current findings by testing a causal link between inner speech and endurance performance and by applying the dual-task method to a novel area of top-down control. In this article, we use 'inner speech' and 'self-talk' interchangeably to refer to self-directed verbalisations with an important difference being that 'self-talk' can mean both covert and overt speech directed at the self.

1.1. Verbal rehearsal and cognitive control

The core executive functions include inhibition, interference control, working memory, and cognitive flexibility (Diamond, 2013). Covert language is involved in several executive processes as people use it to control their own behaviour and remind themselves what their task is (Baddeley et al., 2001; Baldo et al., 2005; Dunbar & Sussman, 1995; Emerson & Miyake, 2003; Henson, Hartley, Burgess, Hitch, & Flude, 2003; Tullett & Inzlicht, 2010). These findings are based on the dual-task interference method where participants are asked to perform a primary task (e.g., adding and subtracting numbers) while also performing concurrent interference task (e.g., repeating the word 'the'). Using this method, inner speech has for example been shown to be involved in impulsivity and inhibitive control (Baldo et al., 2005; Dunbar & Sussman, 1995). Tullett and Inzlicht (2010) tested a go/no go task under verbal (repeating the word 'computer' at 2 Hz) and spatial (drawing circles) interference conditions and found that verbal

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interference increased impulsive responding (faster responses, more commission errors, fewer omission errors). There is also evidence to suggest that people use inner speech to cue themselves on what the relevant task is if they have to switch between multiple task rules (Baddeley et al., 2001; Emerson & Miyake, 2003; Goschke, 2000). While the dual-task method has been a very popular tool for testing the role of covert language in various tasks, it has not yet been used specifically to investigate the role of inner speech in motor control (Nedergaard et al., 2022).

Translating these findings to the area of sustained, physical effort, we expect cycling performance to be related to inhibitory control (or response inhibition) via the ability to resist temptations and to resist acting impulsively. In the case of endurance cycling, the impulse to be inhibited is the impulse to stop when the physical exertion becomes uncomfortable. We might also expect inner speech to play a role in sustained, physical effort through behavioural self-cuing whereby participants focus their own attention on the task instead of allowing it to drift away.

1.2. *Self-talk in sport psychology*

Self-talk interventions where athletes are trained in strategic use of overt or covert self-talk generally have positive effects on performance across a range of sports (Hatzigeorgiadis, Zourbanos, Galanis, & Theodorakis, 2011; Tod, Hardy, & Oliver, 2011). In addition, it is a robust finding that (especially endurance) athletes use organic self-talk to a very large extent (Van Raalte, Morrey, Cornelius, & Brewer, 2015) and that they believe it helps them perform better (Nedergaard, Christensen, & Wallentin, 2021). Organic self-talk can be usefully subdivided into 'spontaneous' and 'goal-directed' self-talk (e.g., Latinjak, Zourbanos, López-Ros, & Hatzigeorgiadis, 2014). Spontaneous self-talk refers to uncontrolled and sometimes maladaptive self-talk while goal-directed self-talk is self-talk generated on purpose by the athlete to achieve specific goals. It is still an open question whether inner speech in fact helps control physical performance beyond what athletes believe. Only a few studies to date have directly investigated self-talk in endurance sport through interventions where participants are trained to use specific self-talk phrases (Barwood, Corbett, Wagstaff, McVeigh, & Thelwell, 2015; Blanchfield, Hardy, De Morree, Staiano, & Marcora, 2014; Hamilton, Scott, & MacDougall, 2007; Hatzigeorgiadis et al., 2018; McCormick, Meijen, & Marcora, 2018; Schüler & Langens, 2007; P. J. Wallace, McKinlay, et al., 2017). These intervention studies, therefore, do not typically address organic self-talk (Latinjak, Hatzigeorgiadis, Comoutos, & Hardy, 2019; Van Raalte, Vincent, & Brewer, 2016) which is more frequent and arguably more relevant to non-elite athletes than strategic self-talk is because such athletes rarely have access to dedicated self-talk training. Endurance sport is particularly interesting from a cognitive perspective because it is a real-world example of a situation that intuitively requires a high degree of cognitive control. In the presence of unavoidable fatigue, long-distance runners, cyclists, swimmers, rowers, etc. have to continuously inhibit the prepotent response (slowing down or quitting) in order to fulfil a longer-term goal. These athletes presumably also have rich opportunity for self-talk content as they are often alone with their thoughts for prolonged stretches of time during both training and competition.

There are several unresolved issues with the self-talk intervention studies that warrant further investigations before a causal link between how people talk to themselves and how they perform can be established. First, the studies are often underpowered with only a few participants in each intervention condition. A metaanalysis by Hatzigeorgiadis et al. (2011) suggested that the average effect size of self-talk interventions is a Cohen's d of 0.48. More recent individual intervention studies generally support this estimate (Galanis et al., 2022; Galanis et al., 2019; Walter, Nikoleizig, & Alfermann, 2019). With this kind of medium-sized effect and between-subjects design, an example power analysis suggests that a study would need approximately 69 participants in each group to detect a difference between two intervention groups with a power of 0.8.[1] A sample size such as this has been the exception rather than the rule (Schweizer & Furley, 2016). With fewer participants, there is an increased risk of both false positives – finding an effect that is not truly there – and false negatives – neglecting to find an effect which is in fact present (Świątkowski & Dompnier, 2017). Second, the intervention studies have also in many cases been lacking active control groups and simply compared participants who had undergone self-talk training and participants who had not undergone any training. The inclusion of active control groups is important because of potential placebo effects. Due to the design of most of these intervention studies, it has not been possible to conclude that the self-talk interventions directly caused performance improvement – it could also simply be the case that undergoing any intervention will help, regardless of the content.

1.3. *The present study*

We aimed to apply the dual-task interference method to the question of whether internal verbalisations help people motivate themselves for physical endurance. While no studies to date have used dual-task interference specifically to test the role of inner speech in endurance performance, there *are* dual-task costs associated with a diverse range of physical performance measures such as jump landing performance (Biese et al., 2019), single-leg postural control (Talarico et al., 2017), climbing (Epling, Blakely, Edgar, Russell, & Helton, 2018; Green & Helton, 2011; Woodham, Billinghurst, & Helton, 2016), swimming (Stets, Smith, & Helton, 2020), and running (Blakely, Kemp, & Helton, 2016). Even though there is evidence of dual-task interference between physical and cognitive tasks, the nature of this interference remains underdetermined – the interference tasks could disrupt mental imagery, inner speech, or attentional mechanisms generally. In the present study, we use a dual-task paradigm specifically designed to investigate the contribution of organic inner speech to endurance. This is done by employing a crucial comparison between a verbal interference task and a non-verbal interference task to isolate the specific effect of the *verbality* of the interference and control for general attentional effects.

In designing the present study, we noted that many of the verbal interference methods used in the literature are not suitable for sports. Articulatory suppression (constantly saying 'the' out loud), for example, would introduce a serious confound by interfering with respiration. The simple motor control often used as comparison – foot tapping – would similarly comprise a motor confound. In the first experiment, we therefore used two memory tasks (memory for letters and numbers or memory for locations on a grid). Aside from not interfering with breathing, these interference tasks had the advantage that we were able to assess performance on them to control for trade-off effects (see Nedergaard et al., 2022, for a discussion). However, as can be seen in more detail in section 3.4. Interim Discussion below, the first experiment had some methodological weaknesses, notably that the interference tasks were not continuous. Because of the methodological weaknesses, we conducted a second experiment with verbal and visuospatial 2-back matching tasks as interference tasks. Our preregistered hypotheses for Experiment 1 were as follows:

I. Cycling performance will decrease in both the verbal and non-verbal interference conditions compared to the control condition.
II. If inner speech is required to maximise performance, we expect cycling performance to decrease significantly more in the verbal compared to the non-verbal interference condition.
III. If there is no detectable dual-task effect on cycling performance, we expect to see a trade-off where there is instead a detrimental effect on the verbal or non-verbal simultaneous task.

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[1] This sample size analysis was conducted for a two-tailed, two-sample t-test with alpha = 0.05 using the *pwr* library in R (Champely, 2020).

We preregistered an additional fourth hypothesis which is solely discussed in the supplemental materials (https://doi.org/10.1016/j.psychsport.2023.102472): ‘Participants who indicate high self-talk frequency and efficacy in the questionnaire will be more negatively affected by the verbal distraction task than other participants.’

2. Experiment 1: method

To ensure transparency and accountability, we preregistered this study on the Open Science Framework (OSF). We chose to aim for approximately 50 participants as this seemed reasonable given our within-subjects design and the moderate effect sizes found in the verbal interference literature (Brysbaert, 2019; Nedergaard et al., 2022; Schweizer & Furley, 2016). For other interference studies related to physical control, the sizes of the interference effects have been in the $d = 0.3$ to $d = 0.7$ range (Biese et al., 2019; Talarico et al., 2017). Simulated analyses further indicated that 50 participants would be sufficient to detect an effect size of $d = 0.4$ (the estimated ‘smallest effect size of interest’; Brysbaert, 2019) (script available on OSF). Repeated measures designs such as ours require fewer participants than the between-groups designs used in the majority of intervention studies.

2.1. Participants

The project received ethical approval from both the Institutional Review Board at Aarhus University and the Human Subjects Committee at the Cognition and Behavior Lab at Aarhus University. Informed consent was provided. We recruited 49 participants from the participant pool attached to Cognition and Behavior Lab. Participants were all above 18 years of age, normally exercised at least twice a week, and reported no known heart conditions (median age = 24 y; range = 18 to 76 y; 29 men and 20 women). Especially the exercise requirement constrains the generalisability of our results as there may be different relationships between inner speech and physical performance for people who do not exercise regularly. However, we chose to implement this requirement to avoid unnecessary risk to participants. Given the wide age range, relative gender balance, and variety of nationalities (31 Danish and 18 non-Danish), we believe our results are relatively generalisable. Participants received 90 DKK as compensation for their time. Participants were asked to measure their resting heart rate prior to the experiment. Nine participants had not measured this, so it was estimated based on their age, gender, and exercise frequency (see Quer, Gouda, Galarnyk, Topol, & Steinhubl, 2020; Reimers, Knapp, & Reimers, 2018).

2.2. Materials

Transparency and openness. All data and PsychoPy code for the experiment can be accessed at the Open Science Framework (https://osf.io/uk2y4/?view_only=e82a1f2ff4ad4e4cb056b370fc83cd69). The data for Experiment 1 were collected in 2020.

Cycling. We ran the experiment using custom-written software in PsychoPy version 3.2.4 (Peirce, 2007). The exercise bike was a Titan Fitness model SB550 Prestige adjusted to Level 14 resistance (piloting had shown that this level of resistance suited the widest range of participants). We used a CatEye Velo 7 cycling computer (CatEye, Osaka, Japan) attached to the exercise bike to measure meters per trial.

Heart rate. We used a Charge 2 FitBit (Fitbit, San Francisco, California, USA) wristband to measure heart rate during the experiment. While wrist-worn heart rate monitors are not as accurate as chest-worn monitors, we opted for the wrist-worn monitor for convenience – we did not need high-fidelity accuracy but simply to have a way of making sure that participants were putting in effort. Benedetto et al. (2018) tested the accuracy of the FitBit Charge 2 wristband and found that it had a modest bias in measuring heart rate at −5.9 bpm (95%CI: −6.1 to −5.6 bpm). We therefore added 5.9 bpm to all heart rate measures. We were unable to retrieve heart rate data from eight participants, so their heart rate data were excluded from subsequent analyses. All participants were instructed to cycle as fast as they could on each cycling trial and at least reach 70% of their heart rate reserve. We calculated 70% of the individual participant’s heart rate reserve with the following formula (adapted from Tanaka, Monahan, & Seals, 2001):

$$HR_{target} = ((208 - 0.7 * age) - HR_{rest}) * 0.7 + HR_{rest}$$

Analysis. All analyses were conducted in R version 4.1.3 (R Core Team, 2022) and RStudio version 2022.02.3. All plots were drawn with *ggplot2* (Wickham, 2016) and all linear models were constructed with *lme4* (Bates, Mächler, Bolker, & Walker, 2015) and *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017).

2.3. Procedure

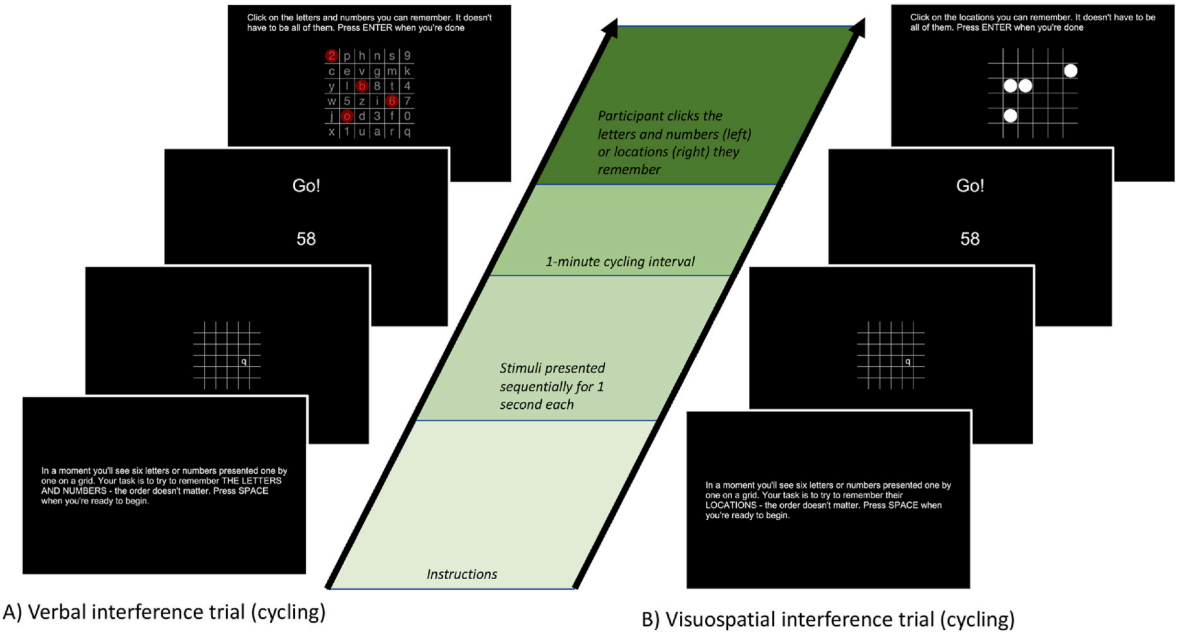
After a brief warm-up (which also served to illustrate the amount of physical effort required to reach 70% of the heart rate reserve) and an introduction to the experimental set-up, participants completed 24 1-min trials (12 rest and 12 cycling, interleaved). Previous studies have indicated that a 1 min-sprint is a sufficient duration to require endurance control (Craig, Pyke, & Norton, 1989; Martin, Davidson, & Pardyjak, 2007). See also Figure 1 for a sketch. During each 1-min trial, participants were asked to rehearse and remember either the locations of six letters and numbers on a grid (visuospatial) or the letters and numbers themselves (verbal). A third of the trials were control trials where participants did not have to remember anything and no stimuli were presented on the screen. The stimuli were presented in the same way regardless of the verbal or visuospatial nature of the memory task: Six letters and numbers were randomly selected by the computer and appeared sequentially for 1 s each. After the stimuli were presented, the program counted down from three and started a 1-min countdown on the computer screen for the duration of the trial. When the countdown had finished, participants had as much time as they wanted to click on either the locations they remembered (visuospatial trial) or the letters and numbers they remembered (verbal trial). When responding after verbal interference trials, the letters and numbers appeared in new locations that were unrelated to the locations in which they were originally presented.

3. Experiment 1: results

3.1. Descriptive statistics

Heart rate. The heartrate data was low-pass filtered using a Butterworth filter with an order of 5 and a cut-off frequency of 0.05 Hz (20s) using he ‘filtfilt’ and ‘butter’ functions from R package *gsignal* (Van Boxtel & et al., 2021). We used the ‘findpeaks’ function from the R package *pracma* to determine both peaks and troughs in heart rate (Borchers, 2021). Out of a total of 473 valid cycling trials (see above), participants reached the target of 70% maximal heart rate on 326 trials (68.9%) and did not reach the target on 147 trials. An independent samples t-tests indicated no difference between trials where the target was reached and where the target was not reached for memory performance ($t(198.12) = -1.365, p = .174$). A chi-squared test also confirmed that there was no difference between interference conditions in terms of the proportion of trials on which the heart-rate target was reached ($\chi^2(2) = 0.26, p = .876$). As is evident from Figure 2 below, there was a large difference (>2 SDs) between heart rate peaks during cycling and heart rate troughs during rest. Given the very short restoration time (less than 1 min), we can therefore be confident that participants did indeed put sufficient pressure on themselves during cycling trials to demand a certain degree of executive control. We decided to retain all trials. For each of the subsequently reported tests, we also tested whether the effects were different between trials where the target was reached and where it was not – this was never the case.

Interference tasks. Participants performed better on the verbal



Click on the letters and numbers you can remember. It doesn't have to be all of them. Press ENTER when you're done

In a moment you'll see six letters or numbers presented one by one on a grid. Your task is to try to remember THE LETTERS AND NUMBERS - the order doesn't matter. Press SPACE when you're ready to begin.

Click on the locations you can remember. It doesn't have to be all of them. Press ENTER when you're done

In a moment you'll see six letters or numbers presented one by one on a grid. Your task is to try to remember their LOCATIONS - the order doesn't matter. Press SPACE when you're ready to begin.

Figure 1. Schematic of the procedure in Experiment 1. Figure 1A on the left shows a cycling trial with verbal interference while Figure 1B on the right shows a cycling trial with visuospatial interference.

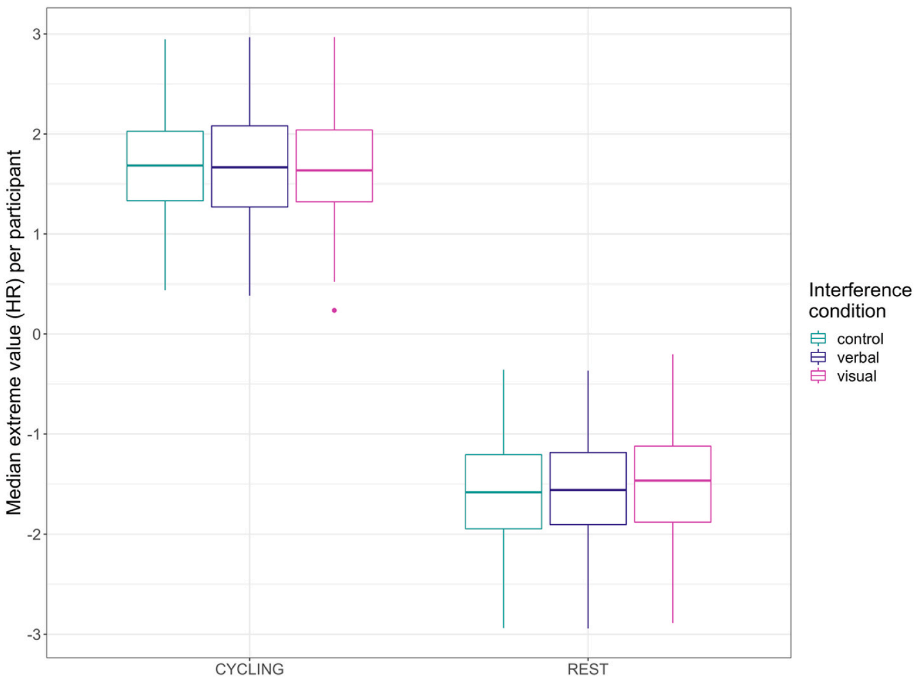


Figure 2. Boxplot showing z-scored heart rate during cycling versus rest in the three interference conditions. The upper and lower hinges correspond to the first and third quartiles, and the central tendency line indicates the median. The upper and lower whiskers extend to a distance of 1.5 * the inter-quartile range (the middle half of the distribution).

Table 1
Performance on the interference tasks during cycling and rest.

Interference condition	Cycling condition	Mean % success	Median % success	SD of % success
verbal	REST	0.86	1	0.21
verbal	CYCLING	0.84	1	0.24
visual	REST	0.54	0.5	0.28
visual	CYCLING	0.52	0.5	0.27

interference task than on the visuospatial interference task. See Table 1 for an overview of participants' performance on the memory tasks during cycling intervals and rest intervals and Figure 3 for a visualisation of the same. To test whether participants' performance was above chance, we simulated 100000 trials of six 'clicks' with a $\frac{6}{36}$ probability of each click being correct. This probability is higher than it should be as participants in the actual experiment sampled without replacement but this is to allow for the fact that participants could change their mind about their responses. Through this procedure, we

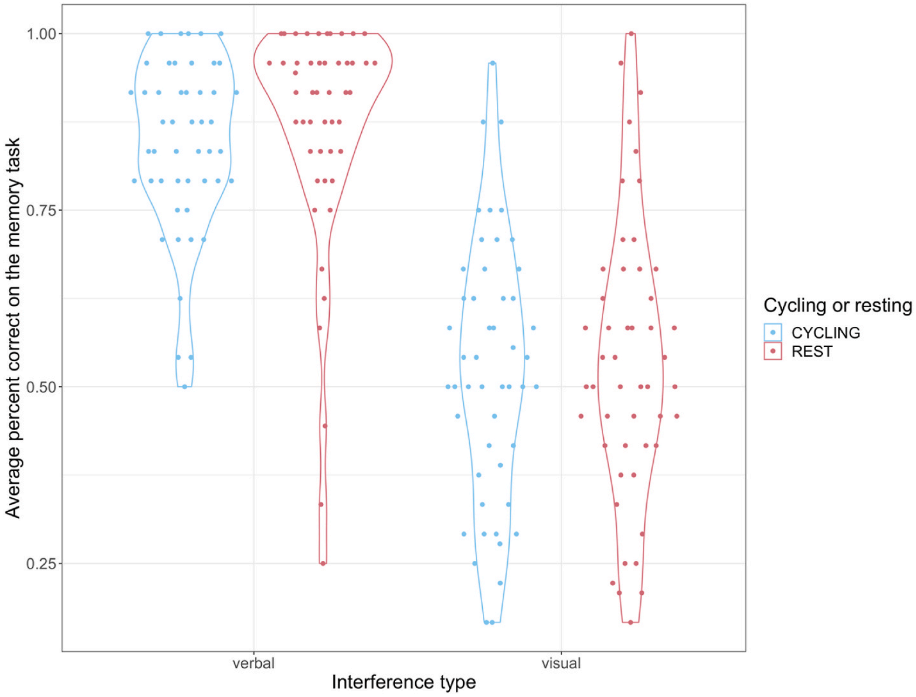


Figure 3. Violin and scatter plot showing participants' performance on the two interference tasks during cycling and rest trials.

established that participants should get one correct click on average each trial if they picked six randomly (average success = 0.17). The simulated baseline distribution indicated that a trial was significantly above chance ($p < .05$) if it had 3 or more correct clicks. A Wilcoxon rank sum test of the difference between the simulated means and memory performance from the experiment showed that performance was significantly above chance on both the visuospatial interference task ($W = 5156398$, $p < .001$) and the verbal interference task ($W = 954200$, $p < .001$). We conducted this non-parametric test as the data were not normally distributed.

Cycling performance. Participants generally cycled furthest in the control condition (M = 214.77 m) followed by the visuospatial interference condition (M = 213.31 m) and the verbal interference condition (M = 212.60 m). See also Figure 4. We scaled the meters cycled according to the individual participant's mean distance cycled to control for individual fitness levels. These scaled meters are used in subsequent

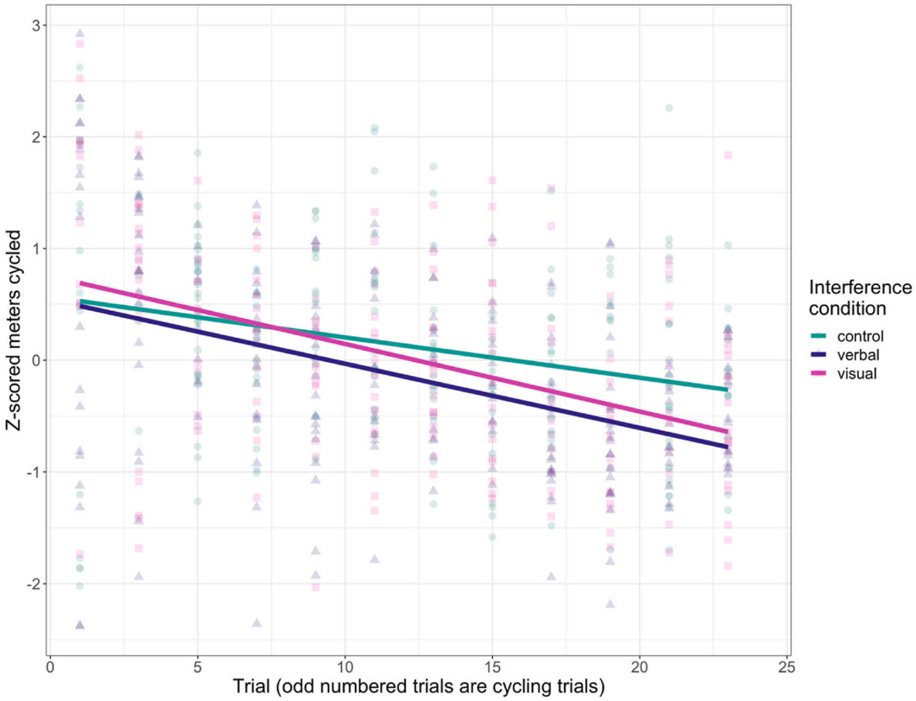


Figure 4. Plot showing participants' z-scored cycling performance across the entire experiment (12 cycling trials and 12 resting trials). The three lines represent linear models of performance during verbal interference, visuospatial interference, and a no-interference control condition. Points indicate individual performance on a given trial.

analyses and models, both because it allowed us to control for differences in fitness levels and because the scaled meters met normality assumptions and the untransformed meters cycled did not. This transformation was not included in the preregistration for Experiment 1.

3.2. *Preregistered linear mixed models*

Dual-task condition predicting cycling performance. We conducted a linear mixed model of dual-task condition predicting z-scored meters cycled including random intercepts for participants and random slopes for trial. This model suggested that the participants cycled significantly faster in the control condition than in the verbal interference condition ($\beta = 0.27$; $SE = 0.10$; $t(432.51) = 2.85$; $p < .001$; see also Figure 4). There was no significant difference between either the visuospatial interference condition and the verbal interference condition ($p = .10$) or between visuospatial interference and the control condition ($p = .227$). Cohen's *d* for the difference between verbal interference and control trials was 0.29 while Cohen's *d* for the difference between verbal and visual interference trials was 0.22. We calculated effect sizes using the 'cohen.d' function from the *effsize* package in R (Torchiano, 2020).

3.3. *Trade-off between interference task and cycling performance*

To ascertain whether there was a trade-off between the interference tasks and cycling performance, we conducted linear mixed model with z-scored meters cycled and interference condition predicting z-scored accuracy on the interference tasks. This model included random slopes over trials per participant. There was evidence that participants performed less well in the visual interference condition compared to the verbal interference condition ($\beta = -1.07$, $SE = 0.08$, $t(333.16) = -13.22$, $p < .001$ – see Figure 3). However, there was no effect of z-scored meters cycled on interference task performance ($p = .230$) and no significant interaction between interference condition and z-scored meters cycled ($p = .573$). See Figure 5.

3.4. *Interim discussion*

As hypothesised, we found that verbal interference had a detrimental effect on cycling performance. This effect, however, was smaller than anticipated in our power analysis and only statistically significant when comparing against the no interference condition and not against the visuospatial condition. There may be different reasons for this. The first option to consider, of course, is that our hypothesis about the involvement of inner speech in physical exercise is wrong. However, given previous findings reviewed in the introduction and the fact that we find a nominal effect pointing in the right direction, we are reluctant to accept this without further considerations. Unfortunately, we also observed a difference in task difficulty for the two interference tasks, resulting in ceiling effects for performance on the verbal interference task, which were not found for the visuospatial interference task (see Table 1). The confounding difference in attentional demand between the two tasks could have led to an underestimation of the effect of verbal interference relative to visual interference. The visual presentation of the stimuli in the beginning of the trial may also have enabled a non-verbal storage strategy that did not involve the articulatory system, thus not interfering as strongly with inner speech as expected. Alternatively, participants might have been able to use some sort of long-term storage which also allowed them to continue their use of their inner voice during the experiment to some degree. Lastly, the visuospatial task might have been so difficult that participants down-prioritised it relative to the task of enhancing cycling performance. The latter, however, is not supported by the data. Performance on the visual memory task was well above chance level as established through simulations, and second, there was no evidence for a trade-off between interference task and cycling.

If the effect of verbal interference found in this experiment is real and robust, then a more continuous interference task should cause a larger effect of verbal interference. Thus, we decided to conduct a follow-up experiment with continuous interference tasks during the cycling trial. This yields the added benefit of allowing us to make conceptual comparisons between effects of different kinds of interference tasks which has rarely been done in previous research (Bek, Blades, Siegal, & Varley,

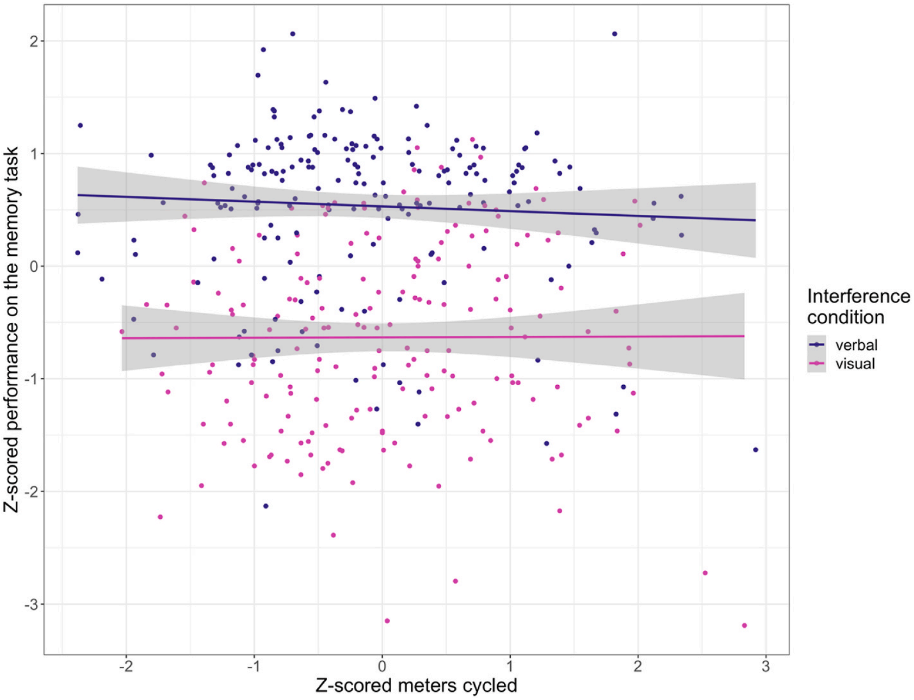


Figure 5. Scatterplot showing the correlation between meters cycled (scaled according to individual participant) and performance on the verbal and visuospatial memory tasks (also scaled according to individual participant). No signs of systematic trade-offs were found. Shaded areas indicate 95% confidence intervals.

2009, 2013; Nedergaard et al., 2022; Piccardi et al., 2020; Roberson & Davidoff, 2000). In Experiment 2, we also measured ECG with electrodes to get more accurate physiological measures than those obtained from the FitBit2 wristband and used a cadence sensor attached to the bike to get more fine-grained performance data.

4. Experiment 2: method

We once again preregistered this study on the Open Science Framework. Our hypotheses were the same as for Experiment 1. We aimed for approximately 50 participants again for the same reasons as detailed in the Method section for Experiment 1, and because we hypothesised that continuous interference would yield a stronger effect in the verbal versus visuospatial interference contrast.

4.1. Participants

The project received ethical approval from both the Institutional Review Board at Aarhus University and the Human Subjects Committee at the Cognition and Behavior Lab at Aarhus University. We recruited 50 participants from the participant pool attached to Cognition and Behavior Lab. Informed consent was provided. Participants were all above 18 years of age, normally exercised at least twice a week, and had no known heart conditions (median age = 25 y, range = 18 to 36 y; 32 men, 17 women, and one who preferred not to disclose their gender). Given the relative gender balance, and variety of nationalities (30 Danish and 20 non-Danish), we believe our results are relatively generalisable. Participants received 110 DKK as compensation for their time (more than in Experiment 1 because the improved physiological measures took longer to set up). Ten participants had not measured their resting heart rate prior to the experiment so it was estimated based on their age, gender, and exercise frequency (see Quer et al., 2020; Reimers et al., 2018).

4.2. Materials

Transparency and openness. All data and PsychoPy code for the experiment can be accessed at the Open Science Framework (https://osf.io/uk2y4/?view_only=e82a1f2ff4ad4e4cb056b370fc83cd69). The data for Experiment 2 were collected in 2022.

Cycling. We ran the experiment using custom-written software in PsychoPy version 3.2.4. The exercise bike was a Titan Fitness model SB550 Prestige adjusted to Level 14 resistance (identical to Experiment 1). We used a Wahoo RPM Cadence Censor v1.54.0.10 (Wahoo Fitness, Atlanta, Georgia, USA) attached to the exercise bike to measure cadence.

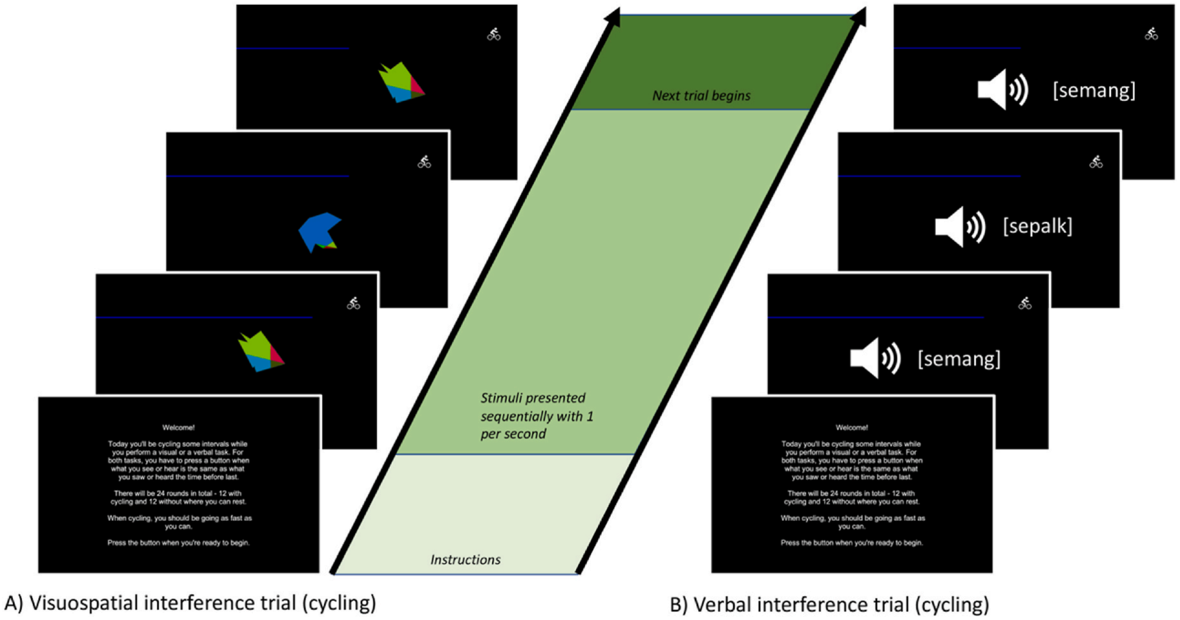
Heart rate. We used a BIOPAC BioNomadix system (BIOPAC Systems, Goleta, California, USA) to measure heart rate and respiration during Experiment 2. All participants were instructed to reach 70% of their heart rate reserve on each cycling trial. We calculated 70% of the individual participant's heart rate reserve with the following formula (Tanaka et al., 2001):

$$HR_{target} = ((208 - 0.7 * age) - HR_{rest}) * 0.7 + HR_{rest}$$

Analysis. All analyses were conducted in R version 4.1.3 (R Core Team, 2022) and RStudio version 2022.02.3. All plots were drawn with *ggplot2* (Wickham, 2016) and all linear models were constructed with *lme4* (Bates et al., 2015) and *lmerTest* (Kuznetsova et al., 2017).

4.3. Procedure

After a brief warm-up (which also served to illustrate the amount of physical effort required to reach 70% of the heart rate reserve) and an introduction to the experiment set-up, participants completed 24 1-min trials (12 rest and 12 cycling, interleaved). See also Figure 6 for a sketch. During each 1-min interference trial, participants performed a 2-back memory task. They were asked to pay attention to either nonsense words played every other second (verbal interference) or coloured, geometric figures appearing in different locations on the screen every other second (visuospatial interference). Participants had to press a button (attached to the handles of the stationary bike) if the word they heard or the figure they saw was the same as the one presented two words/figures previously. A third of the trials were control trials where participants did not have to remember anything and no stimuli were presented on the screen. They were, however, required to press the button every 10 s to control for motor interference. Instead of a countdown of the seconds presented on the screen with numbers as in Experiment 1, Experiment 2 counted down the trial duration with a blue bar at the top of the screen. The cue to whether participants were in a



Welcome!

Today you'll be cycling some intervals while you perform a visual or a verbal task. For both tasks, you have to press a button when what you see or hear is the same as what you saw or heard the time before last.

There will be 24 rounds in total - 12 with cycling and 12 without where you can rest.

When cycling, you should be going as fast as you can.

Press the button when you're ready to begin.

Welcome!

Today you'll be cycling some intervals while you perform a visual or a verbal task. For both tasks, you have to press a button when what you see or hear is the same as what you saw or heard the time before last.

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When cycling, you should be going as fast as you can.

Press the button when you're ready to begin.

A) Visuospatial interference trial (cycling)

B) Verbal interference trial (cycling)

Figure 6. Schematic of the procedure in Experiment 2. Figure 6A on the left shows a cycling trial with visuospatial interference while Figure 6B on the right shows a cycling trial with verbal interference. Both show examples of 2-back matches. Note that the 2-back matching nonsense words were only presented auditorily in the actual experiment.

cycling trial or a resting trial was also non-verbal in Experiment 2 contrasting with Experiment 1.

5. Experiment 2: results

5.1. Descriptive statistics

Heart rate. The heartrate data was low-pass filtered using a Butterworth filter with an order of 5 and a cut-off frequency of 0.05 Hz (20s) using he 'filtfilt' and 'butter' functions from R package *gsignal* (Van Boxtel & et al., 2021). We used the 'findpeaks' function from the R package *pracma* to determine both peaks and troughs in heart rate (Borchers, 2021). Due to technical difficulties, we excluded heart rate data from one participant. Out of a total of 586 valid cycling trials, participants reached the target of 70% maximal heart rate on 444 trials (75.8%) and did not reach the target on 142 trials. An independent samples t-tests indicated no difference between trials where the target was reached and where the target was not reached for *d'* memory performance ($t(129.56) = 0.74, p = .459$). A chi-squared test also confirmed that there was no difference between interference conditions in terms of the proportion of trials on which the target was reached ($\chi^2(2) = 0.13, p = .938$). As is evident from Figure 7 below, there was a large difference (>2 SDs) between heart rate peaks during cycling and heart rate troughs during rest. Given the very short restoration time (less than 1 min), we can therefore be confident that participants did indeed put sufficient pressure on themselves during cycling trials to demand a certain degree of executive control. We decided to retain all trials. For each of the subsequently reported tests, we also tested whether the effects were different between trials where the target was reached and where it was not – this was never the case.

Interference tasks. Performance was measured using *d'* (d-prime), which takes both hits and false alarms into account (Macmillan & Creelman, 2005). Participants performed better on the verbal interference task than on the visuospatial interference task. See Table 2 for an overview of participants' performance on the memory tasks during cycling intervals and rest intervals and Figure 8 for a visualisation of the same. On many individual trials, participants had 100% hit rate which creates infinite *d'* estimates. To prevent this, we used the adjustment (Hautus, 1995; Stanislaw & Todorov, 1999) built into the 'dprime' function from the *psycho* package in R (Makowski, 2018).

Table 2
Performance on the interference tasks during cycling and rest.

Interference condition	Cycling condition	Mean hits out of 6	Mean false alarms out of 24	Mean d'
verbal	REST	4.54	0.84	2.41
verbal	CYCLING	4.56	1.34	2.28
visual	REST	3.85	1.13	2.02
visual	CYCLING	4.06	1.40	2.06

Cycling performance. Participants cycled fastest in the control condition (M = 99.9 revolutions per minute) followed by the visuospatial interference condition (M = 96.6 revolutions per minute) and the verbal interference condition (M = 93.9 revolutions per minute). See also Figure 9. As in Experiment 1, we scaled the cycling performance according to the individual participant to control for individual fitness levels (see also preregistration).

5.2. Preregistered linear mixed models

Dual-task condition predicting cycling performance. Our linear mixed model with scaled cycling cadence (equivalent to cycled meters) as dependent variable and condition as independent variable, including random slopes for trial by participant revealed that the participants in the verbal interference condition cycled with significantly lower cadence than in the control interference condition ($\beta = 0.54$; $SE = 0.05$; $t(501.98) = 10.28$; $p < .001$) and the visuospatial interference condition ($\beta = 0.25$; $SE = 0.05$; $t(501.84) = 4.72$; $p < .001$). Note that the coefficients are positive because the verbal interference condition was treated as the baseline condition. Changing the contrasts so that the visuospatial condition was treated as baseline indicated that there was also a significant difference the visuospatial interference condition and control condition ($\beta = 0.29$; $SE = 0.05$; $t(502.53) = 5.51$; $p < .001$). Cohen's *d* for the difference between verbal interference and control trials was 1.00 while Cohen's *d* for the difference between verbal and visual interference trials was 0.43. We calculated effect sizes using the 'cohen.d' function from the *effsize* package in R (Torchiano, 2020).

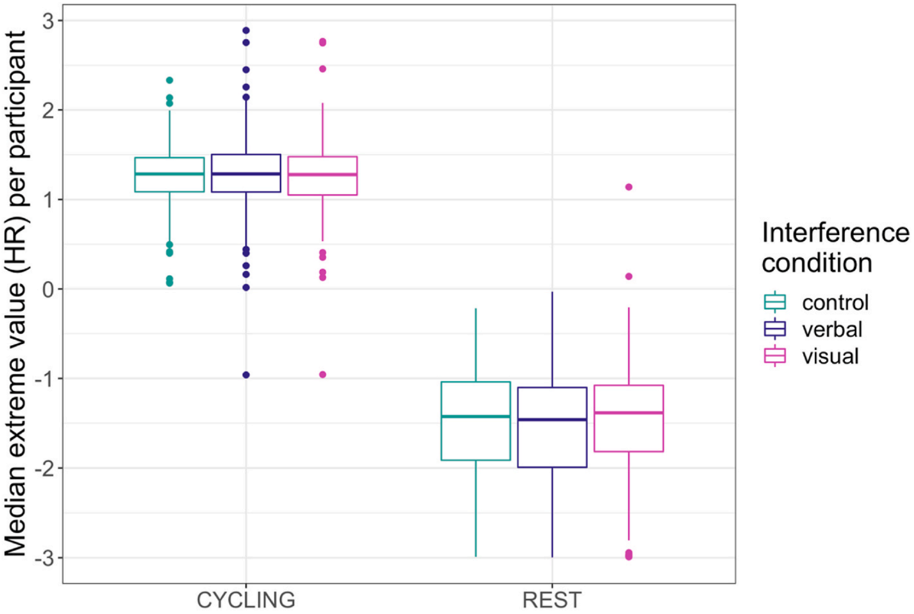

Figure 7. Boxplot showing z-scored heart rate during cycling versus rest in the three interference conditions. The upper and lower hinges correspond to the first and third quartiles, and the central tendency line indicates the median. The upper and lower whiskers extend to a distance of 1.5 * the inter-quartile range (the middle half of the distribution).

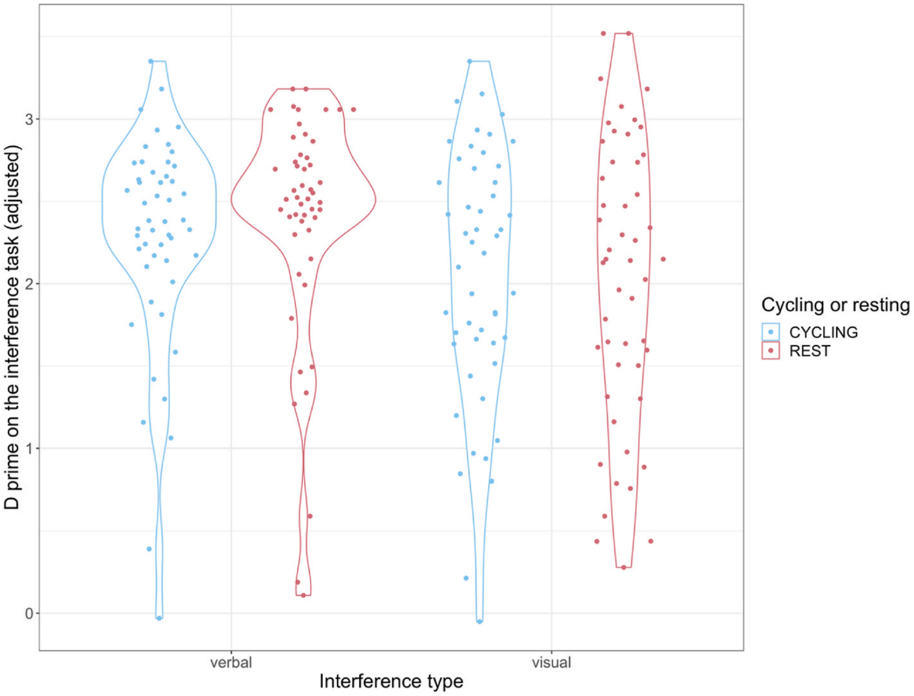

Figure 8. Violin and jitter plot showing participants' performance (d') on the two interference tasks during cycling and break trials. Values of d' are adjusted to prevent infinite values (see main text). Absolute perfect performance across all trials would equal a d' of 4.5.

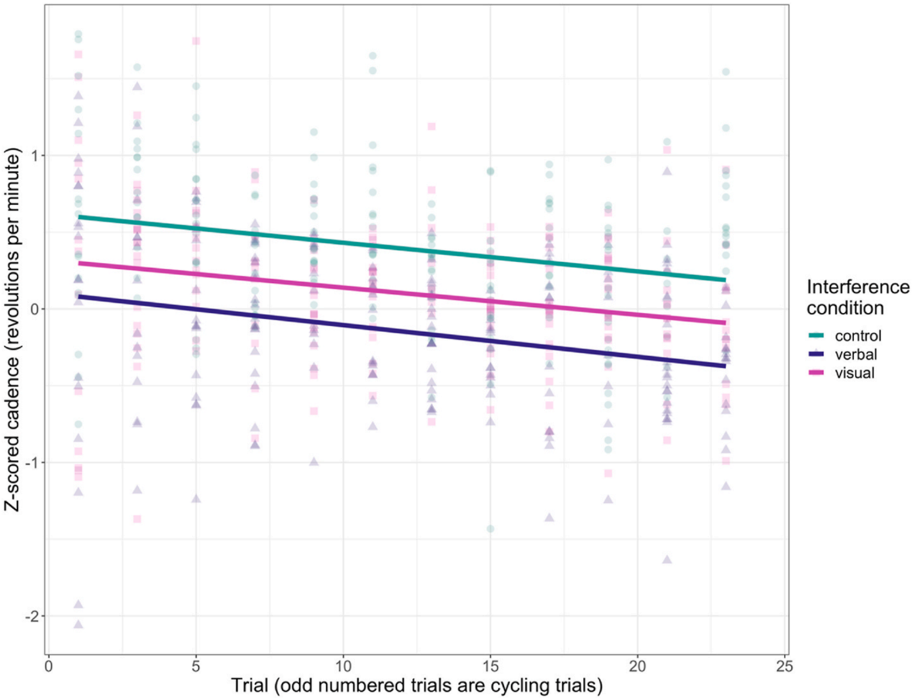

Figure 9. Plot showing participants' cycling performance across the entire experiment (12 cycling trials and 12 resting trials), scaled by their individual mean cadence. The three lines represent performance during verbal interference, visuospatial interference, and a no-interference control condition. Points indicate individual performance on a given trial.

5.3. *Trade-off between cycling performance and 2-back matching performance*

To ascertain whether there was a trade-off between the interference tasks and cycling performance, we conducted linear mixed model with z-scored cadence and interference condition predicting *d'* on the interference tasks. This model included a random slope over trials per participant as well as random intercepts for each participant. There was evidence that participants performed less well on the interference task if they cycled faster ($\beta = -0.22$, $SE = 0.10$; $t(296.86) = -2.283$, $p = .023$), and participants also performed less well in the visual interference condition compared to the verbal interference condition ($\beta = -0.17$, *SE*

= 0.07, $t(298.53) = -2.56$, $p = .011$). However, there was no significant interaction between interference condition and z-scored cadence (p = .368). See Figure 10. This indicates that the two interference tasks were equally susceptible to trade-off.

6. Discussion

Across two experiments, we found a general effect of cognitive interference on physical endurance performance as well as a specific effect of verbal interference suggesting a causal role for inner speech. We tested the influence of four different interference tasks on cycling performance (a "one off" visuospatial memory task, a "one off" verbal memory task, a continuous verbal 2-back matching task, and a continuous visual 2-back matching task). In Experiment 1, which used one-off memory-based interference, only verbal interference had a significant detrimental effect compared with the no-interference control condition ($d = 0.29$). This effect was nominally larger than the visuospatial effect, but the verbal interference effect ($d = 0.22$) was not significantly different from the effect of visuospatial interference with the used sample size. In Experiment 2, which used a continuous interference task with fewer possibilities for adopting non-verbal task strategies, the detrimental effect of verbal interference on cycling performance was stronger than the visuospatial interference ($d = 0.43$). These results are in line with our main hypothesis.

6.1. *Dual-task interference and cognitive control*

As discussed in the Introduction, covert language may be involved in endurance performance as a vehicle for behavioural self-cuing, inhibitive control, and motivation. For example, the prepotent response to muscle fatigue and being out of breath is to stop the physical exertion – in this experiment, participants had to exert control to keep going, and we hypothesised that this control would to some extent be influenced by the ability to use inner speech. Participants could use many different inner speech strategies – regardless of which one, disrupting self-talk should disrupt control of the physical performance. We argue that under verbal interference, participants were less able to use their inner voice to focus their attention on the task demands and inhibit their propensity to slow down, and this had detrimental effects on their cycling performance. This is in line with previous dual-task literature suggesting that participants respond more impulsively (i.e., faster and with more errors) under verbal distraction conditions (Dunbar & Sussman, 1995; Nedergaard et al., 2022; Tullett & Inzlicht, 2010). In our experiment, the impulse would be to slow down.

One of the reasons why we decided to change the interference tasks from Experiment 1 to Experiment 2 was that the verbal interference task was substantially easier than the visuospatial interference task in Experiment 1. There was also no trade-off between cycling performance and interference task performance in Experiment 1, perhaps indicating that the interference tasks were not demanding enough. The issue with the difference in difficulty between the verbal and the visuospatial interference tasks was not quite solved in Experiment 2, although neither was at ceiling (in contrast to Experiment 1 where verbal interference task performance was near-perfect). To assess potentially problematic trade-off effects in more detail, we examined whether interference task condition and cycling performance predicted interference task performance. We found that the verbal interference task was indeed easier than the visuospatial interference task and that interference task performance decreased with increased cycling performance. However, there was no significant interaction between cycling performance and interference task condition, indicating that the trade-off was the same between interference task conditions. The absence of an interaction effect makes a direct comparison between their effects on cycling performance more reliable. The fact that the verbal interference task was easier than the visual indicates that we may still be underestimating the effect size of the direct comparison.

6.2. *Effects of self-talk in sport*

The present results provide an important additional perspective to the discussion on the effects of self-talk in sport. Existing dual-task studies investigating the involvement of cognitive functions in sport were ill-suited to answering our present questions as they were not designed to test verbal involvement specifically. Intervention studies on endurance sport have found that self-talk helps improve performance (Barwood et al., 2015; Blanchfield et al., 2014; Hamilton et al., 2007; Hatzigeorgiadis et al., 2018; McCormick et al., 2018; Schüler & Langens, 2007; P. J. Wallace, McKinlay, et al., 2017). Because of the design of

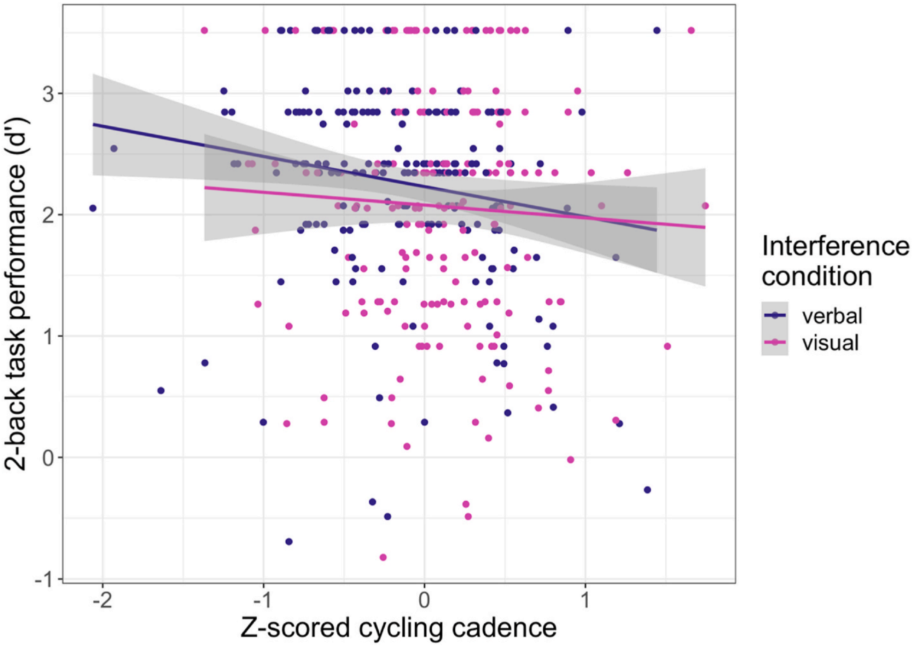

Figure 10. Scatterplot showing the correlation between meters cycled (scaled according to individual participant) and performance on the verbal and visuospatial memory tasks (d'). Shaded areas indicate 95% confidence intervals.

most of these intervention studies, it has not been possible to conclude that the self-talk interventions directly caused performance improvement – it could also simply be the case that undergoing any intervention helped, regardless of the content. The present study provides support for the claim that self-talk indeed has a direct causal role in performance.

A natural way to follow up on the present study would be to examine the role of inner speech in real endurance sports situations (such as marathons, triathlons, etc.) where it may be even more important how athletes talk to themselves. There is convincing evidence that marathon runners, for example, *believe* that self-talk helps them perform better (McCormick et al., 2018; Nedergaard et al., 2021; Schüler & Langens, 2007; Van Raalte et al., 2015) but evidence from interventions concerning whether it actually helps is mixed. As athletes generally differ in what kinds of self-talk helps them based on the type of sport (Theodorakis, Weinberg, Natsis, Douma, & Kazakas, 2000), their level of expertise (Nedergaard et al., 2021), and whether the setting is competition or training (Hatzigeorgiadis, Galanis, Zourbanos, & Theodorakis, 2014), we would expect interference to be differentially disruptive as well. For example, novices appear to benefit more from self-talk which yields the prediction that they would be more adversely affected by verbal interference (Nedergaard et al., 2021).

6.3. Limitations and future directions

The dual-task interference paradigm employed in the present study provides a promising avenue for future research in sport psychology. We were interested in organic self-talk and thus did not ask our participants to say specific words or phrases to themselves the way it is usually done in intervention studies (Latinjak et al., 2019), but studies with a combination of self-talk training and verbal interference hold much potential. If one is interested in the effects of inner speech on behaviour and more particularly effects of the form and content of inner speech, it is informative to combine methods down-regulating language (such as verbal interference) with methods up-regulating language (such as self-talk training) (Nedergaard et al., 2022). Studies designed to inhibit linguistic processes, such as the present one, leave un-answered questions about what it is about inner speech that helps. Studies designed to increase specific ways of using language such as self-talk interventions are conversely limited in the causal claims they can make. The present study also contributes to the dual-task interference literature more generally by comparing effects of different types of interference (memory and continuous 2-back matching in this case). The fact that our continuous interference tasks yielded larger effects than the one-off memory interference tasks will be relevant for the choice of interference type in future studies.

7. Conclusion

The present study tested cycling performance during 1-min intervals under verbal and visuospatial interference conditions across two experiments using different kinds of interference tasks. While both interference conditions affected cycling performance negatively compared with a control condition, verbal interference was significantly worse than the control condition in Experiment 1 and worse than both the control and the visuospatial interference conditions in Experiment 2. Together, our experiments indicate that the inner voice plays an important role in the top-down control of physical performance.

Author note

All authors declare that they have no competing interests. All experiment data, code, and preregistrations can be accessed at https://osf.io/uk2y4/?view_only=e82a1f2ff4ad4e4cb056b370fc83cd69.

Declaration of competing interest

None.

Data availability

I have shared my data and code on the Open Science Framework (see link on title page).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2023.102472.

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