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Cognitive load causes kinematic changes in both elite and non-elite rowers

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ABSTRACT

The current motor literature suggests that extraneous cognitive load may affect performance and kinematics in a primary motor task. A common response to increased cognitive demand, as observed in past studies, might be to reduce movement complexity and revert to previously learned movement patterns, in line with the progression-regression hypothesis. However, according to several accounts of automaticity, motor experts should be able to cope with dual task demands without detriment to their performance and kinematics. To test this, we conducted an experiment asking elite and non-elite rowers to use a rowing ergometer under conditions of varying task load. We employed single-task conditions with low cognitive load (i.e., rowing only) and dual-task conditions with high cognitive load (i.e., rowing and solving arithmetic problems). The results of the cognitive load manipulations were mostly in line with our hypotheses. Overall, participants reduced movement complexity, for example by reverting towards tighter coupling of kinematic events, in their dual-task performance as compared to single-task performance. The between-group kinematic differences were less clear. In contradiction to our hypotheses, we found no significant interaction between skill level and cognitive load, suggesting that the rowers' kinematics were affected by cognitive load irrespective of skill level. Overall, our findings contradict several past findings and automaticity theories, and suggest that attentional resources are required for optimal sports performance.

1. Introduction

Athletes' dual tasking is associated with a performance cost (Moreira, Dieguez, Bredt, & Praça, 2021). That is, adding extraneous cognitive load during a motor task will typically lead to worse performance, as compared to normal or single-task conditions. Sports performance has proven to be suboptimal, for example, when soccer players solve arithmetic problems while juggling a ball (Laurin & Finez, 2020). In this case, it appeared that both the juggling and arithmetic tasks required attentional resources, which are limited (e.g., Musslick & Cohen, 2021; Pashler, 1994). When faced with "information overload" (Fitts & Posner, 1967, p. 34), we tend to ignore

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parts of the task-relevant information for an indeterminate amount of time. This might explain why extraneous cognitive load has led to reduced accuracy (e.g., Schaefer & Scornaienchi, 2020), balance (e.g., Albertsen, Ghédira, Gracies, & Hutin, 2017; Van Biesen, Jacobs, McCulloch, Janssens, & Vanlandewijck, 2018), and smoothness (e.g., Kim et al., 2013) in motor performance.

Given our limited capacity to attend to task-relevant stimuli, an adaptive response to extraneous cognitive load is to free up attentional resources by altering our behavior (see Broadbent et al., 2023; Higuchi, Imanaka, & Hatayama, 2002). One way to accomplish this is to reduce the quantity or complexity of ongoing motor execution. For example, Oh and LaPointe (2017) found that healthy individuals walked with shorter stride lengths in dual-task conditions, as compared to a single-task condition. This seems to be in line with the *progression-regression hypothesis* (Fuchs, 1962). After years of progression and learning how to walk, our gait is typically characterized by long and confident strides. However, when we are *stressed* by increased performance demands (e.g., a secondary cognitive task; Fuchs, 1962), we may regress towards older patterns. In the case of walking, this means that we revert to the relatively short steps that are typical of children learning how to walk (or an adult re-learning to walk after suffering from a stroke; Nascimento, de Oliveira, Ada, Michaelsen, & Teixeira-Salmela, 2015). In addition to the stress associated with increased cognitive demands, stressors may come from anxiety-inducing stimuli which can, like cognitive load, divert attentional resources away from the motor task and affect movement kinematics (Eysenck, Derakshan, Santos, & Calvo, 2007; Higuchi et al., 2002). Accordingly, the presence of an audience, rewards, or punishment has led to reduced motion lengths in sports tasks, such as shorter backswing (Tanaka & Sekiya, 2010a) or follow-through (Tanaka & Sekiya, 2010b) in golf putting.

One may also reduce movement complexity by reverting to a tighter *coupling* of kinematic events, for example by moving limbs more simultaneously (Gray, 2020b; Higuchi et al., 2002). Following practice, athletes typically progress from tight coupling, such as the novice rower extending their legs and pulling the handle at the same time, to a more de-coupled technique, such as the rower using legs to initiate the action before trunk and arms finish the stroke sequence (Buckeridge, Bull, & McGregor, 2015; Soper & Hume, 2004). As this rowing example suggests, athletes' motion sequence usually goes from proximal (near the body center) to distal (away from the body center) areas to allow the larger muscles near the body center to initiate the action, resulting in effective power development (e.g., Fleisig, Barrentine, Escamilla, & Andrews, 1996; Hatsopoulos, Olmedo, Takahashi, Danion, & Latash, 2010). However, task-related stress or *pressure* (i.e., situational factors that increase the importance of a performance; Baumeister, 1984) may cause athletes to revert to a tighter coupling between body segments. Orn (2017) asked experienced basketball players to shoot free throws under normal practice circumstances (i.e., with no added pressure) or stressful conditions. In the latter case, participants were told that a video camera filmed their shots, that the recordings would be analyzed by an expert later, and that they competed with others for prize money. Under such stress, participants demonstrated greater temporal coupling between peak velocities in their knee and elbow, as compared to throwing under normal circumstances. Again, this seems to be in line with the progression-regression hypothesis: under pressure, the athletes' kinematics became more “novice-like” (Orn, 2017, p. i).

However, it is unclear whether *motor experts*, such as elite athletes who have trained for years and regularly compete at higher levels in their sport (Swann, Moran, & Piggott, 2015), are prone to dual-task costs and kinematic changes due to cognitive load. Gray (2004, Experiment 1), for example, recruited baseball players of different levels, including an expert group of Division 1–A college players with >15 years of competitive experience on average, to engage in a virtual batting task. In a single-task condition, the participants swung at either “fastballs” or “slow balls” that a simulated pitcher threw at them. In a dual-task condition, the players did the same batting task while they also listened to tones and responded by saying “high” or “low”, depending on the tone's frequency. The results suggested that, compared to the single-task condition, the dual-task condition had no significant impact on the experts' batting performance and kinematics. Accordingly, research has found no negative effects of dual tasking or distractors on experienced athletes' performance in rugby (Gabbett & Abernethy, 2012; Gabbett, Wake, & Abernethy, 2011) and golf (Herrebrøden, Grotterød, & Hystad, 2019; Herrebrøden, Sand Sæbø, & Hystad, 2017; Land & Tenenbaum, 2012).

The latter findings on experts may be due to the cognitive and neural consequences of practice. As motor actions are repeated over and over, they may become *automatized* to the point where they require little attentional resources (Furley & Memmert, 2010; Furley, Schweizer, & Bertrams, 2015; Gray, 2015). The elite athlete, then, may pay relatively little attention to the motor task and have spare capacity for extraneous cognitive tasks. This is supported by neuroscientific research and, specifically, the *neural efficiency hypothesis*, suggesting that cortical activity is reduced in skilled motor performance with practice (e.g., Cheng et al., 2015, 2023; Filho, Dobersek, & Husselman, 2021). Mental effort, or the intensive use of our attentional capacity (Kahneman, 1973), may primarily be needed when we use working memory resources to store and manipulate information in the short term. If elite athletes do not depend on such mental effort in their primary sports performance, but rather rely on the relatively effortless retrieval of information from procedural long-term memory, one would not expect to find substantial detriment due to extraneous cognitive load. Indeed, *self-focus* (Christensen, Sutton, & McIlwain, 2015) or *turning towards* (Gray, 2020a) theories suggest that attention to ongoing motor execution can be harmful to elite athletes' performance. Conversely, *distraction* (Christensen et al., 2015) or *turning away* (Gray, 2020a) theories, predicting suboptimal performance if attention is drawn away from ongoing task execution, have found less support in previous studies on motor experts in dual-task contexts. These opposing frameworks will be further addressed in the Discussion section.

In sum, studies and theories suggest that elite athletes' concern might be excessive attention, as opposed to a lack of attention directed at the motor task at hand. However, the existing literature has several shortcomings. First, the overall load and task complexity in past studies have typically been relatively modest (for reviews, see Christensen et al., 2015; Wulf & Shea, 2002). This is well illustrated in Gray's (2004) dual-task study. The motor task (i.e., hitting at two types of baseball pitches) was far less complex than a real-world baseball batting situation, and the extraneous cognitive task (i.e., responding to low- or high-frequency tones) may not have been particularly taxing on the performer's cognitive resources. Second, many studies have primarily concerned themselves with performance outcome measures (e.g., golf putts hit or missed; Land & Tenenbaum, 2012). Underlying factors, such as kinematic data, may provide richer information on which aspects of the motor performance, if any, are affected by cognitive load. Third, research on expert or elite athletes is relatively scarce, and many studies that have claimed to recruit such samples have involved participants that are far away from competing at the highest level in their sport (Swann et al., 2015). Thus, less is known about how cognitive load affects those who depend the most on their motor performance, such as professionals or elite athletes.

In the current study, elite and non-elite rowers were asked to use a rowing ergometer under varying physical demands and cognitive load (i.e., single-task and dual-task rowing). Ergometer rowing represents a continuous and physically demanding sports task, as opposed to the discrete and relatively static tasks that are overrepresented in research, such as golf putting (e.g., Perrey & Besson, 2018). To effectively develop power during the drive phase, skilled rowers use long strokes (Černe, Kamnik, Vesnicer, Žganec Gros, & Munih, 2013; Ingham, Whyte, Jones, & Nevill, 2002) with a proximal-to-distal kinematic chain to allow the powerful leg muscles to drive the boat and extend the knees before the trunk and the arms take over (Buckeridge et al., 2015; Soper & Hume, 2004). During the recovery phase, this kinematic chain is mirrored as skilled rowers return with arms and trunk first, before the legs bend, preparing the rower for another drive phase (Kleshnev, 2022)–see Fig. 1. Smooth actions and balance will help the boat move efficiently on the water (see Smith & Loschner, 2002). In sum, rowing represents a complex motor skill due to the many biomechanical degrees of freedom, placing high demands on timing and coordination between lower and upper limbs (e.g., Cordo & Gurfinkel, 2004; Wulf & Shea, 2002). While these requirements are somewhat different on ergometers than on the water, we used a *dynamic* ergometer that resembles several aspects of on-water rowing to a closer extent than the more conventional *static* ergometers (e.g., Elliott, Lyttle, & Birkett, 2002; Kleshnev, 2005).

We predicted the following characteristics in single-task conditions (low cognitive load) relative to dual-task conditions (high cognitive load), and elites relative to non-elites:

1) Greater de-coupling between leg extension and trunk extension during the drive phase, and between leg flexion and trunk flexion in the recovery phase.
2) Greater stroke lengths.
3) Greater smoothness (i.e., motion fluidity).
4) Greater balance (i.e., less variability in the seat's tilting motion).

We further hypothesized that the effects of cognitive load would be stronger on non-elites than elites' kinematics. The physical load involved either low or moderate intensity, mainly due to physiological measurements that are not currently reported, and we formed no hypothesis regarding physical load manipulations. Hence, the effects of physical load will be reported as exploratory work and not emphasized in this paper. This study was pre-registered at the Open Science Framework: https://osf.io/94xtk. The current hypotheses were formed as a follow-up to a previous report from the same experiment and the same sample (Herrebrøden, Espeseth, & Bishop, 2023, submitted manuscript) in which we found declined rowing performance in dual-task conditions (high cognitive load) relative to single-task conditions (low cognitive load) across skill levels.

2. Method

2.1. Participants

Eighteen male rowers, nine elite and nine non-elite, participated in this study. The elites were members of Team Norway, the highest-level training group in the Norwegian national team system, preparing for the 2020 Olympic Games in Tokyo. Based on Swann et al.'s (2015) categorization, as well as our elite participants' achievements, they may be classified as Competitive elite, Successful elite, and World-class elite, respectively. Further specifications of the athletes' characteristics and achievements are left out for anonymity reasons. At the time of participation, their average age was 29.67 (*SD* = 6.06) years, and they had an average rowing experience of 14.89 (*SD* = 5.84) years. Their mean height was 190.44 (*SD* = 6.98) cm, and their average weight was 90.89 (*SD* = 7.94) kg.

The non-elites were a group of lower-level rowers, with a mean age of 29.89 (*SD* = 11.70) years and a mean of 4.33 (*SD* = 4.95) years of rowing experience. These rowers were recruited based on the condition of never having won a major national or international

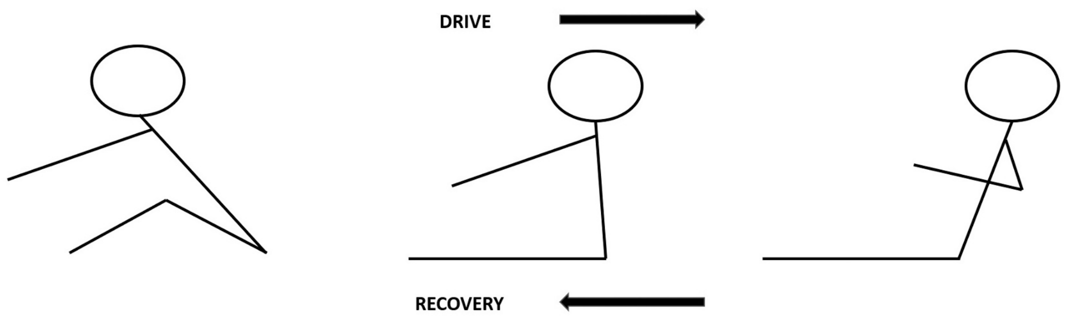

Fig. 1. Rowing technique during the drive (left to right) and recovery (right to left) phases.
Notes. Rowing kinematics with a kinematic chain (i.e., sequential coordination between lower and upper limbs during the respective stroke phases).

competition as an individual rower, and never having represented the Norwegian national rowing team. Lastly, only rowers that could provide a result on a 2000-m (2 K) rowing ergometer race or test, as well as an indication of their current form or physical shape, were included in the current analyses, since this information was used to inform the intensity levels used in our current study (see the next section). The non-elites were on average 187.39 ($SD = 4.44$) cm tall and had a mean weight of 86.56 ($SD = 5.50$) kg.

All participants volunteered to take part in the study without reimbursement or reward, and they all signed informed consent forms. The study was approved by the Norwegian Centre for Research Data (NSD; project identification number 455008).

2.2. Rowing task and load manipulation

This study was conducted in a motion capture laboratory. Participants used a Row Perfect 3 (RP3) Model S (www.rp3rowing.com), a dynamic rowing ergometer mimicking the experience of rowing a sculler (boat) (Kleshnev, 2005). Participation involved three-minute rowing trials for a total of six different conditions with partial counterbalancing, yet only four conditions were included in the current analyses. That is, we currently investigated rowing in a 2 × 2 task design that varied in terms of physical and cognitive load.

Participants rowed with approximately 75% of their expected 2 K racing pace (low physical load) and approximately 85% of their expected 2 K racing pace (high physical load). Expected 2 K racing pace was estimated based on each participant's previous race or test values as well as their indication of current form or physical shape. Although we refer to 85% of race speed as a "high" physical load, this resembles rowing at moderate physical intensities. The reason we did not let participants use higher intensities was the possibility of causing considerable noise to our physiological recordings (see the Measurement section) and potentially affecting participants' ability to deal with the cognitive load.

Participants were asked to row with a constant pace (single-task rowing; low cognitive load) and to row with a constant pace while solving arithmetic problems (dual-task rowing; high cognitive load). Pace could be monitored on a screen in front of them, which provided stroke-by-stroke information about the current *split* (i.e., time spent per 500 m of rowing, given the current pace), stroke rate, and time left of the trial. Arithmetic problems were presented via loudspeakers, and participants had approximately 10 s to respond verbally before the next problem was presented. A beep signaled to the participants that a new problem would follow. The problems required addition (based on Zarjam, Epps, & Lovell, 2012) and multiplication (based on Ahern & Beatty, 1979). Specifically, the following types of problems were presented via pre-recorded sound files, in said order:

1. Addition of one- and two-digit numbers (e.g., 35 + 2)

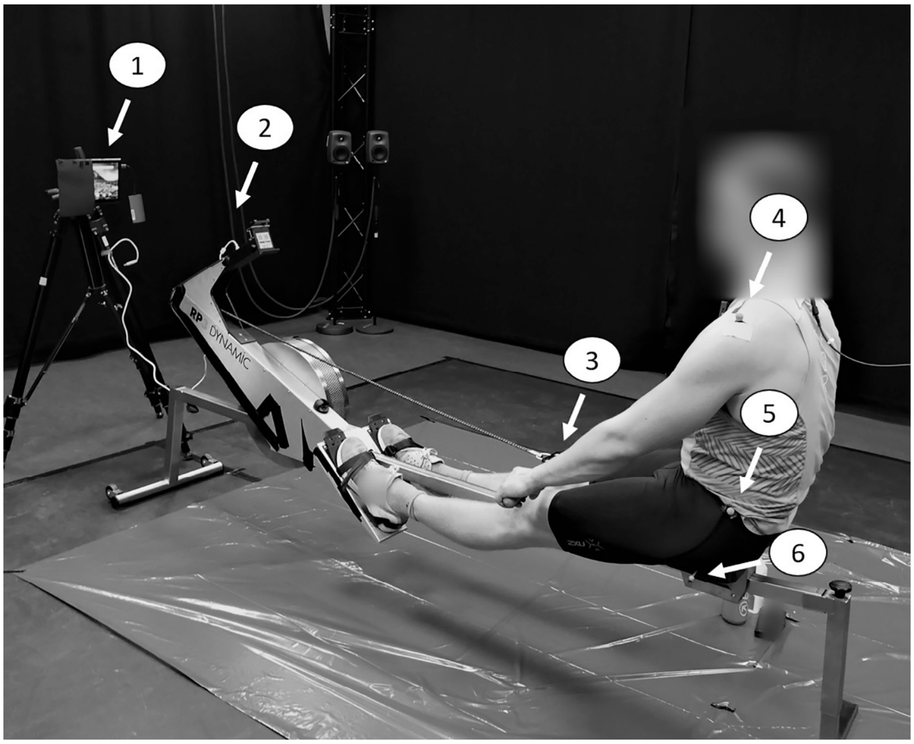

Fig. 2. Photography showing ergometer components and marker locations.
Notes. Numbers indicate the location of the (1) ergometer monitor, (2) frontal part of the rowing ergometer, which moves horizontally as a function of the rower's leg extension/flexion, (3) ergometer handle, (4) shoulder marker, (5) hip marker, and (6) marker on the side of the seat, which moves vertically as a function of seat stability.

2. Addition of one- and two-digit numbers with one carry (e.g., 63 + 9)
3. Addition of two-digit numbers with one carry (e.g., 73 + 42)
4. Multiplication of [digits 6, 7, 8, or 9] by [digits, 12, 13, or 14] (e.g., 8 × 12)
5. Multiplication of [digits 6, 7, 8, or 9] by [digits 16, 17, 18, or 19] (e.g., 9 × 16)
6. Multiplication of [digits 11, 12, 13, 14, or 15] by [digits 16, 17, 18, or 19] (e.g., 15 × 16)

Each dual-task condition consisted of two such series, for a total of 12 problems. All participants responded to the same problems, and no single problem was presented twice to the same individual.

2.3. Measurements

RP3 rowing ergometers provide rich data on performance and rowing mechanics. For the current purposes, we extracted data on stroke length (in cm) from the ergometer output. We also extracted data on split to get a stroke-by-stroke measure of rowing speed in seconds unit (s).

A Qualisys (www.qualisys.com) motion capture system with 11 infrared cameras (Oqus 300 series) was used to explore rowers' kinematics. Reflective markers were attached to bony landmarks on the rowers' shoulders and hips. We also placed markers on the ergometer handle, on the side of the seat (which moves as a function of seat stability), and on the frontal part of the ergometer (which moves as a function of how the user extends or bends their legs). Fig. 2 indicates the location of various markers. The cameras recorded these markers in three dimensions at a sample rate of 240 Hz.

We administered two different questionnaires, both containing one item each that will be used for current manipulation checks. First, the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) was used to measure self-reported effort after each condition, and we currently analyzed participants' ratings on the Mental Demand item. Second, we employed a custom-made questionnaire asking participants the extent to which they attended to various cues during trials. Currently, we report on the extent to which they attended to technical (i.e., rowing-related) task cues.

We also employed other measurements which will not be discussed in this article. Specifically, participants wore eye-tracking glasses, heart rate belts, and electromyography (EMG) sensors. A Canon XF105 video camera recorded the trials from the side. Verbal responses to arithmetic problems were either recorded via the eye-tracking glasses' microphone or a Røde Wireless Go microphone attached to the rower's chest (not interfering with their motion).

2.4. Procedure

Participants started by filling out questionnaires regarding background information, where they were also presented with the pace values (splits) that they would follow in the respective conditions. They were given the option of accepting or changing these values (e.g., due to their current form or other factors). Most participants accepted the proposed pace values, while some made small adjustments to our suggestions. Participants were then equipped with various sensors and markers.

The rowers warmed up in their preferred way. At the beginning of warmup on the ergometer, a sound check was conducted. That is, a pre-recorded sound file presented three numbers that the participant repeated aloud while rowing. This was to ensure that the volume was set loud enough so the rower would hear the arithmetic problems presented in the dual-task conditions, despite the additional sound coming from the ergometer fan.

After some general instructions, participants began their rowing trials. They were presented with specific task instructions ahead of each condition. Each rowing trial was followed by a two-minute break and two questionnaires (described in the previous section).

A short debrief ended the session. Participants were instructed to not share the content of the cognitive load manipulation with other rowers, as we wanted the next participant to be naive to our dual-task conditions.

2.5. Data processing and analysis

Two of the raw data's stroke length values, in two different trials, were considered to be noise and thus the ergometer data for these strokes were manually replaced by missing values.

The motion capture recordings were manually processed in Qualisys Track Manager (version 2021.2). After labeling markers and filling gaps (in cases where the system failed to identify the respective markers), no marker of interest had >10% of missing samples in the recordings of the rowing trials. For shoulders, hips, and handle, we consistently included only the right-side markers for analyses. For the seat, we chose the side marker (left or right) with the least missing data.

A primary interest in the motion capture analyses was to investigate the relationship between leg extension/flexion and trunk extension/flexion during drive and recovery, respectively. To accomplish this, we first identified the samples where shoulders had passed the hips on the horizontal axis. Next, we extracted a measure of how extended the legs were at this moment in time. This dependent variable will, from here on, be referred to as *relative leg extension*. To attain a measure of relative leg extension, we investigated the horizontal motion of the RP3 ergometer's frontal part. This part of the ergometer moves as a function of the rower's leg extension: when extending the knee (during drive) the ergometer front gets pushed away from the rower, while bending the knees (during recovery) brings the front closer to the rower. We thus created a relative score implying how far the legs were extended, based on the positioning of the ergometer front. A score of 100% meant fully extended, relative to the participant's maximum horizontal value for the ergometer front. These values were extracted from the first sample after the shoulder marker had passed the hip marker on the horizontal axis, in both directions (i.e., during drive and recovery, respectively).

Balance was investigated by creating a measure of the stability in the seat's position. The ergometer we used had a loosely fastened (i.e., “wobbly”) seat that allowed a tilting motion, causing the reflexive marker (placed on the side of the seat) to move up and down if the rower leaned towards the sides. Hence, this seat marker's standard deviation on the vertical axis provided a measure of seat instability. These values were converted to negative values to create a measure of seat stability for each trial.

To provide a measure of smoothness, we first used a Savitzky-Golay filter (order = 3, window = 11) to smooth the handle's horizontal motion data, and then calculated velocity and acceleration. The handle’s motion smoothness was operationalized as the ratio of velocity and acceleration (previously conceptualized as a measure of fluidity; Burger, Saarikallio, Luck, Thompson and Toiviainen, 2012) along the horizontal axis.

The first and last 10 s of each trial were excluded from analyses, both for the motion capture recordings and the ergometer data. As our dependent variables, we used the means from our values of interest during the remaining 160 s, that is, the relative leg extension during drive and recovery (as separate variables), motion smoothness (ratio of velocity and acceleration; $\frac{mm/s}{mm/s^2}$), seat stability (in mm), and stroke length (in cm).

In addition to the main kinematic investigations, we conducted exploratory analyses to investigate whether our task manipulations had the intended effects. The dependent variables included rowing speed variability (i.e., standard deviations of split values throughout the trial) as a measure of rowing task performance (since participants were asked to row with a constant pace). The number of arithmetic problems solved correctly served as a measure of cognitive task performance. Self-reported mental effort (i.e., Mental Demand as rated on the NASA-TLX) was an indicator of cognitive load and overall attentional demands. These NASA-TLX scores were converted to percentages, where 100% meant the highest rating possible. As a measure of self-reported attention to rowing technique, participants filled out a custom-made questionnaire to rate the extent to which they attended to technical task cues on a seven-point scale, ranging from “to a very large extent” to “to a very small extent”. For the statistical analyses, the questionnaire’s response options were converted to numbers with 1 indicating “to a very large extent” and 7 indicating “to a very small extent”. Apart from the latter custom-made questionnaire, similar results, and descriptive statistics, will be presented elsewhere in the context of our full experiment (Herrebrøden et al., 2023, submitted manuscript).

The code used for processing data and computing variables can be found on GitHub (https://github.com/henrher/Rowing_EyeTracking), and a full report on our tests of statistical assumptions can be found at the Open Science Framework (https://osf.io/xdhzn/?view_only=ec667a37091742fd8874d11eb1361b41). After the data filtering, no extreme outlier was detected in our kinematic dependent variables. The ANOVA assumptions for normality and equality of variance were met in most cases, albeit with some violations, which might be expected given the small sample size and the number of variables. A series of three-way (2 × 2 × 2) mixed ANOVA analyses were used to investigate the effect of cognitive task load (single task and dual task), physical load (low and high), and skill level (elite and non-elite), as well as potential interactions, on the dependent kinematic variables. The alpha level was set at .05. Generalized Eta Squared (η^2G) was used as a measure of effect sizes, as it allows for comparability between within- and between-subjects effects across different study designs (see Bakeman, 2005). JASP (https://jasp-stats.org/) software was used for analyses.

3. Results

3.1. Manipulation checks

A series of mixed ANOVAs tested the effects of task load and skill level on task performance and attentional demands.

3.1.1. Task performance

A three-way mixed ANOVA was conducted with rowing speed variability as the dependent variable, cognitive load (low and high) and physical load (low and high) as the within-subject factors, and skill level (elite and non-elite) as the between-subject factor. This revealed that speed variability was significantly affected by cognitive load ($F(1, 16) = 17.967$, $p < .001$, $\eta^2G = 0.271$), physical load ($F(1, 16) = 16.329$, $p < .001$, $\eta^2G = 0.180$), and skill level ($F(1, 16) = 27.940$, $p < .001$, $\eta^2G = 0.308$), with no interaction effects. Rowing speed was less variable with low cognitive load ($M = 1.10$ s, $SD = 0.41$ s) than high cognitive load ($M = 1.56$ s, $SD = 0.58$ s), with high physical load ($M = 1.15$ s, $SD = 0.42$ s) as compared to low physical load ($M = 1.50$ s, $SD = 0.60$ s), and in elites ($M = 1.08$ s, $SD = 0.45$ s) as compared to non-elites ($M = 1.58$ s, $SD = 0.52$ s).

A 2 × 2 mixed ANOVA revealed that the amount of correctly solved arithmetic problems was significantly affected by physical load ($F(1, 16) = 7.563$, $p = .014$, $\eta^2G = 0.070$), with no significant impact from skill or interaction between physical load and skill. More problems were solved correctly in the condition of low physical load ($M = 7.89$, $SD = 1.64$) than high physical load ($M = 7.06$, $SD = 1.47$). The minimum number of correctly solved arithmetic problems per trial was five, and the highest score per trial was 11 (out of 12) correct solutions.

To conclude, rowing performance declined as a function of cognitive load, and participants from both skill levels engaged in the secondary arithmetic task while rowing.

3.1.2. Attentional demands

A mixed ANOVA suggested that Mental Demand was significantly affected by cognitive load ($F(1, 16) = 155.680$, $p < .001$, $\eta^2G = 0.742$) as well as an interaction between cognitive load and physical load ($F(1, 16) = 5.245$, $p = .036$, $\eta^2G = 0.031$). Descriptively, high cognitive load ($M = 77.98\%$, $SD = 14.19\%$) was rated as more mentally demanding than low cognitive load ($M = 29.94\%$, $SD =$

15.99%). Pairwise comparisons of all combinations of loads, with Bonferroni corrections, revealed that conditions with high cognitive load were always rated as more demanding than the conditions with low cognitive load, irrespective of physical load ($p < .001$). Further, Mental Demand in the low cognitive load conditions was not significantly different between the low ($M = 25.24\%$, $SD = 17.36\%$) and high physical load conditions ($M = 34.64\%$, $SD = 13.36\%$), $p = .080$. Similarly, the high cognitive load conditions did not differ across low ($M = 78.36\%$, $SD = 12.67\%$) and high physical load ($M = 77.61\%$, $SD = 15.93\%$), $p = 1.000$. There were no significant effects of physical load, skill level, or any other interactions. In sum, Mental Demand ratings on the NASA-TLX appeared to be affected primarily by cognitive load.

One elite participant was given the wrong version of our attentional focus questionnaire (asking the extent to which the rowers attended to technical task cues) after one of the trials, and his responses were therefore excluded from this part of the manipulation check. A mixed ANOVA based on responses from the remaining participants ($n = 17$) revealed that technique focus was significantly affected by cognitive load ($F(1, 15) = 63.679$, $p < .001$, $\eta^2G = 0.385$), with no effect of physical load, skill, or interactions. Descriptively, on a scale of 1 (to a very large extent) to 7 (to a very small extent), the rowers replied that their technical focus was more prominent during low cognitive load ($M = 2.94$, $SD = 1.25$) than high cognitive load ($M = 5.09$, $SD = 1.56$).

In sum, the dual-task condition appeared to fulfill its intended effect, as participants across skill groups reported greater mental demand and less attention to technical rowing cues as a function of cognitive load.

3.2. Rowing kinematics

Table 1 provides an overview of our main dependent variables of interest, including their means and standard deviations across all participants ($n = 18$), and intercorrelations.

A three-way mixed ANOVA was carried out with participants' relative leg extension during the drive phase as the dependent variable, cognitive task load and physical load as the within-participants factors, and skill level as the fixed between-participants factor. Results indicated that relative leg extension during drive was significantly affected by cognitive load ($F(1, 16) = 7.137$, $p = .017$, $\eta^2G = 0.008$) and physical load ($F(1, 16) = 34.223$, $p < .001$, $\eta^2G = 0.015$). Descriptively, relative leg extension decreased from low cognitive load ($M = 72.95\%$, $SD = 9.28\%$) to high cognitive load ($M = 71.32\%$, $SD = 10.68\%$), and from low physical load ($M = 73.23\%$, $SD = 9.70\%$) to high physical load ($M = 71.05\%$, $SD = 10.24\%$). The difference between elites ($M = 76.16\%$, $SD = 7.88\%$) and non-elites ($M = 68.11\%$, $SD = 10.30\%$) did not reach statistical significance ($F(1, 16) = 3.355$, $p = .086$, $\eta^2G = 0.169$), and there were no significant interaction effects between cognitive load and physical load ($F(1, 16) = 1.762$, $p = .203$, $\eta^2G < 0.001$), cognitive load and skill ($F(1, 16) = 1.761$, $p = .203$, $\eta^2G = 0.002$), physical load and skill ($F(1, 16) = 0.209$, $p = .653$, $\eta^2G < 0.001$), or the three-way interaction ($F(1, 16) = 3.027$, $p = .101$, $\eta^2G < 0.001$).

As for the recovery phase, a mixed ANOVA revealed that relative leg extension was significantly affected by cognitive load ($F(1, 16) = 4.731$, $p = .045$, $\eta^2G = 0.030$), physical load ($F(1, 16) = 27.124$, $p < .001$, $\eta^2G = 0.023$), and skill level ($F(1, 16) = 22.888$, $p < .001$, $\eta^2G = 0.555$), respectively. The relative leg extension during recovery was greater with low cognitive load ($M = 76.63\%$, $SD = 8.13\%$) than high cognitive load ($M = 74.48\%$, $SD = 10.45\%$), with low physical load ($M = 76.49\%$, $SD = 9.16\%$) than high physical load ($M = 74.62\%$, $SD = 9.59\%$), and in elites ($M = 82.36\%$, $SD = 4.54\%$) than non-elites ($M = 68.75\%$, $SD = 7.86\%$). No significant interactions were found between cognitive load and physical load ($F(1, 16) = 0.006$, $p = .937$, $\eta^2G < 0.001$), cognitive load and skill ($F(1, 16) = 3.728$, $p = .071$, $\eta^2G = 0.024$), physical load and skill ($F(1, 16) = 0.011$, $p = .918$, $\eta^2G < 0.001$), or the three interaction terms ($F(1, 16) = 1.022$, $p = .327$, $\eta^2G < 0.001$). Fig. 3 displays relative leg extension across cognitive load and skill levels in the respective rowing phases.

A mixed ANOVA further revealed that stroke lengths were significantly affected by cognitive load ($F(1, 16) = 4.965$, $p = .041$, $\eta^2G = 0.012$) and physical load ($F(1, 16) = 14.479$, $p = .002$, $\eta^2G = 0.005$). Load had an inverse effect on stroke lengths, as they were longer with low cognitive load ($M = 133.62$ cm, $SD = 6.73$ cm) than high cognitive load ($M = 132.21$ cm, $SD = 6.95$ cm), and with low physical load ($M = 133.35$ cm, $SD = 6.87$ cm) than high physical load ($M = 132.48$ cm, $SD = 6.86$ cm). The stroke lengths in elites ($M = 135.08$ cm, $SD = 6.41$ cm) and non-elites ($M = 130.76$ cm, $SD = 6.63$ cm) were not significantly different ($F(1, 16) = 1.965$, $p = .180$, $\eta^2G = 0.104$). Further, there were no significant interactions between cognitive load and physical load ($F(1, 16) = 0.431$, $p = .521$, $\eta^2G < 0.001$), cognitive load and skill ($F(1, 16) = 3.843$, $p = .068$, $\eta^2G = 0.009$), physical load and skill ($F(1, 16) = 0.308$, $p = .587$, $\eta^2G < 0.001$), or the three variables combined ($F(1, 16) = 0.021$, $p = .886$, $\eta^2G < 0.001$).

The analysis on motion smoothness revealed a main effect of cognitive load ($F(1, 16) = 4.865$, $p = .042$, $\eta^2G = 0.002$), a main effect of physical load ($F(1, 16) = 65.459$, $p < .001$, $\eta^2G = 0.044$), and interaction of physical load and skill level ($F(1, 16) = 6.092$, $p = .025$,

Table 1
Descriptive statistics and correlations for all kinematic variables.

Variable	*M*	*SD*	1	2	3	4	5
Leg extension, drive (%)	72.14	9.97	–				
Leg extension, recovery (%)	75.55	9.36	0.73***	–			
Stroke length (cm)	132.92	6.83	−0.05	0.20	–		
Smoothness $\left(\frac{mm/s}{mm/s^2}\right)$	0.19	0.04	0.40***	0.40***	0.19	–	
Seat stability (mm)	−1.89	0.87	0.50***	0.78***	0.31**	0.37**	–

* $p < .05$, ** $p < .01$, *** $p < .001$.

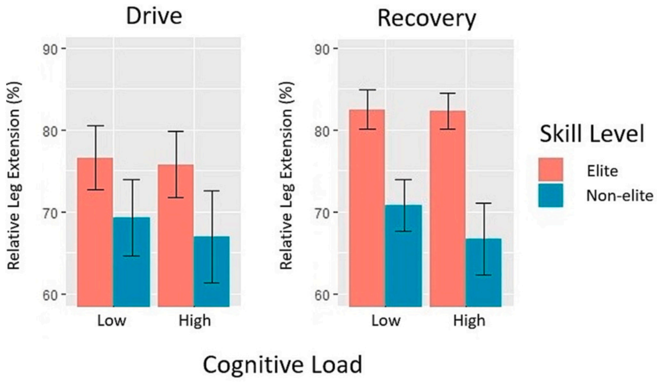

Fig. 3. Relative leg extension across cognitive load and skill levels.
Notes. Error bars indicate 95% confidence intervals.

$\eta^2G = 0.004$). Motion smoothness was greater with low cognitive load ($M = 0.192$, $SD = 0.040$) than high cognitive load ($M = 0.189$, $SD = 0.039$). Post-hoc *t*-tests with Bonferroni correction revealed that elite rowers demonstrated significantly more smoothness ($p < .001$) in the low ($M = 0.211$, $SD = 0.045$) compared to high physical load condition ($M = 0.190$, $SD = 0.043$), and also that the non-elites were significantly smoother ($p = .007$) in the low ($M = 0.186$, $SD = 0.033$) compared to the high physical load condition ($M = 0.175$, $SD = 0.029$). Hence, physical load appeared to reduce fluidity in both skill levels, albeit somewhat more clearly in the elites. The main effect of skill was non-significant ($F(1, 16) = 1.201$, $p = .289$, $\eta^2G = 0.068$), as were the interaction effects of cognitive load and skill level ($F(1, 16) = 0.555$, $p = .467$, $\eta^2G < 0.001$), cognitive load and physical load ($F(1, 16) = 2.193$, $p = .158$, $\eta^2G < 0.001$), and cognitive load, physical load, and skill level ($F(1, 16) = 3.733$, $p = .071$, $\eta^2G = 0.002$).

A final mixed ANOVA suggested that seat stability was only affected by skill level ($F(1, 16) = 64.347$, $p < .001$, $\eta^2G = 0.762$). Elites ($M = -1.14$ mm, $SD = 0.25$ mm) demonstrated greater stability than non-elites ($M = -2.65$ mm, $SD = 0.56$ mm). No significant effects were found for cognitive load ($F(1, 16) = 0.088$, $p = .770$, $\eta^2G < 0.001$) or physical load ($F(1, 16) = 1.773$, $p = .202$, $\eta^2G = 0.003$), nor were there any significant interactions between cognitive and physical load ($F(1, 16) = 2.429$, $p = .139$, $\eta^2G = 0.004$), cognitive load and skill ($F(1, 16) = 0.027$, $p = .872$, $\eta^2G < 0.001$), physical load and skill ($F(1, 16) = 3.523$, $p = .079$, $\eta^2G = 0.005$), or the three-way interaction ($F(1, 16) = 0.010$, $p = .923$, $\eta^2G < 0.001$).

4. Discussion

This study investigated the effects of cognitive load on rowing kinematics across skill levels and physical intensities. We hypothesized that dual-task conditions, in which rowers used an ergometer while solving arithmetic problems, would be associated with changes in rowing technique, relative to single-task rowing conditions. The kinematic variables investigated were fundamental aspects of rowing technique, namely, the de-coupling of leg extension/flexion and trunk extension/flexion, stroke lengths, motion smoothness, and seat stability (i.e., balance). It was further hypothesized that elite rowers would possess these key characteristics to a greater extent and that their technique would be less affected by cognitive load than non-elites. The findings mainly supported our hypotheses for cognitive load, as dual tasking led to the predicted kinematic changes relative to single-task rowing, with the exception of seat stability which was mainly affected by skill level. However, several differences between elites and non-elites were unclear, and cognitive load appeared to affect both skill groups. Overall, our results contradict several past findings and challenge certain theoretical frameworks.

Various kinematic changes were observed due to cognitive load in our study. For one, going from single-task rowing to dual-task rowing led participants to demonstrate less leg extension before the trunk rotated during both the drive and recovery phases of the rowing cycle. Second, the overall technical execution became more compressed, as evidenced by reduced stroke lengths under high cognitive load. These findings corroborate previous studies that have used stress or pressure manipulations during motor tasks (Oh & LaPointe, 2017; Orn, 2017; Tanaka & Sekiya, 2010a, 2010b). Tighter coupling or reduced motion duration may be interpreted as strategies for making the action less complex and relying less on online cognitive control (Higuchi et al., 2002). This may free up the attentional capacity needed to handle the extraneous cognitive task. We also observed less motion smoothness under increased task demands. This may be due to the relatively coupled and compressed movement kinematics we observed. That is, if rowers use short stroke lengths and move limbs rather simultaneously, power may be developed more abruptly, causing a less fluid action, than if the limb's contributions were de-coupled and spread over a longer time period. One would think that this may lead to reduced balance, in line with our hypothesis. However, seat stability was unaffected by cognitive load. One possible explanation is that the reduced stroke lengths countered the reduced smoothness, resulting in maintained balance. That is, the rowers moved less in both horizontal directions, as suggested by their reduced stroke lengths, enabling their center of gravity to stay relatively close to the center of the seat. This may have countered any instability due to less fluid motion. Indeed, compressed motion length may be a strategy to preserve coordination under stress (see Deschamps, Nourrit, Caillou, & Delignières, 2004). The overall kinematic pattern observed under high cognitive load may have been an adaptive response to the cognitive challenge, leaving participants with a relatively stable posture and cognitive capacity preserved for mental work.

Our findings deviate from several past studies that have failed to find detrimental effects of dual tasking on performance or kinematics in skilled athletes (e.g., Gabbett et al., 2011; Gray, 2004; Land & Tenenbaum, 2012). Methodologically speaking, this might be explained by overall task complexity. In terms of the motor aspect, ergometer rowing represents a biomechanically complex skill that requires coordination between more limbs than, say, the commonly researched task of golf putting. Duckworth et al. (2021) found that rowing ergometer performance (i.e., power output) was more negatively affected by cognitive load when participants engaged in full-body ergometer rowing, as compared to upper-body rowing (i.e., with legs remaining fully extended). It seems likely that complex actions, such as those requiring coordination between lower and upper body motion, require more cognitive resources, and are thus more negatively affected by extraneous cognitive load, than simple actions (see Wulf & Shea, 2002). In terms of the extraneous cognitive element, we used a demanding arithmetic task of varying difficulty. This requires effortful processing, whereas easier tasks such as the tone recognition paradigm commonly used in dual-task sport studies (e.g., Gabbett et al., 2011; Gray, 2004) should demand far less from athletes' attentional resources. Hence, past studies may not have sufficiently taxed the performer's attentional capacity to properly test the effects of cognitive distraction.

The lack of significant interaction effects suggests that cognitive load affected both elites and non-elites. This is noteworthy since the kinematic variables we explored included fundamental aspects of rowing technique, which one might expect to be ingrained in elites' automatic movement patterns (see Fitts, 1964; Logan, 1986). Several accounts of automaticity, including the Reinvestment theory (Masters & Maxwell, 2008) and the Constrained Action Hypothesis (Wulf, McNevin, & Shea, 2001), appear to predict results that differ from our current findings (see also Christensen et al., 2015). These particular frameworks may be labeled as *self-focus* (Christensen et al., 2015) or *turning inwards* (Gray, 2020a) theories, as they suggest that attention to motor task execution can lead to performance failure. To avoid that, the motor performer may be advised to focus on the external environment (Wulf et al., 2001), such as the dartboard's center when throwing darts (Marchant, Clough, Crawshaw, & Levy, 2009), or use "distraction techniques" (Masters & Maxwell, 2008, p. 174), for example by saying a random letter upon hearing a signal during golf putting (Land & Tenenbaum, 2012). In the current study, distracting dual-task conditions did indeed cause rowers to reduce their attention to ongoing motor task execution, relative to single-task conditions, as suggested by our manipulation checks. However, dual tasking also led to kinematic changes and worse performance. Hence, the self-focus or turning inwards theories offer little explanation of our findings.

Conversely, *distraction* (Christensen et al., 2015) or *turning away* (Gray, 2020a) theories predict performance failure if attentional resources directed towards the task at hand are insufficient. In other words, they advocate an important role for cognitive control during task performance, and they appear to be more in line with the current effects of cognitive load. Such theories would include, for example, the Attentional Control Theory (Eysenck et al., 2007). The plausible explanation for our findings in line with this theory would be that, under the distracting circumstances of our dual task, the performers attended to rowing-irrelevant stimuli (i.e., the arithmetic task). And while participants increased their mental effort (as evidenced by our manipulation checks), it appeared insufficient to optimally deal with rowing *and* the extraneous cognitive load, resulting in reduced effectiveness on the rowing task (see Eysenck et al., 2007). Seemingly, the rowers adapted to cognitive load by reducing the complexity of the motor component and using kinematic solutions that may have demanded less online attentional control (i.e., via short stroke lengths and coupled limb motion). In the past literature, the failure mechanism proposed by Attentional Control Theory has been linked to situations of performance anxiety, as anxious performers may tend to direct their attention towards task-irrelevant, often threatening stimuli (e.g., an audience), and thus reduce attention to the task at hand (see Eysenck et al., 2007). Overall, the theory appears able to explain failure due to both cognitive load and pressure in sports settings.

In absolute or descriptive terms, elites appeared to possess the hypothesized technical characteristics to differentiate themselves from non-elites, but several between-group comparisons came out non-significant. This could be due to the sample size or variance in our data. Yet, it could also speak to the difficulty of finding the "optimal technique" (see Soper & Hume, 2004). Scarborough, Bassett, Mayer, and Berkson (2020), for example, failed to find the expected proximal to distal sequencing pattern on a consistent basis in baseball pitchers. Accordingly, a previous study on Norwegian national team rowers revealed substantial variability in the coordination between lower-body and upper-body segments (Becker et al., 2019).

Unsurprisingly, however, elite rowers demonstrated greater balance on the ergometer, as measured by seat stability. Further, we did find a clear difference in the kinematic sequencing pattern during the recovery part of the rowing cycle. That is, elites demonstrated a clearer de-coupling between leg flexion and trunk flexion than non-elites. In rowing terms, they had a clearer *rock-over*, by keeping the legs relatively straight as the trunk leaned forward past the hips, during the recovery. As the terminology suggests, this phase is the relatively slow and relaxed part of the rowing cycle, as rowers spend more time and less force here than in the drive phase (Hohmuth, Schwensow, Malberg, & Schmidt, 2023). Hence, recovery is the rower's prime opportunity to consciously process task-relevant information and plan the next stroke. Since elites demonstrated a more proficient rock-over (as compared to non-elites), which declined when attentional resources were directed elsewhere (during the dual-task), it seems plausible that elites took the opportunity to exert cognitive control over their kinematic events during the recovery phase. This could be in line with the *long-term working memory* model (Ericsson & Kintsch, 1995), developed to explain cognition in experts. This model suggests that, while experts have substantial knowledge stored in long-term memory, which may be retrieved in a relatively effortless fashion (see Kahneman, 1973), they also rely on working memory (i.e., storage and manipulation of concurrent information) and attention to contextual information in order to access the appropriate knowledge. However, to explicitly test this theory in a sports context seems challenging (see Foroughi, Werner, Barragán, & Boehm-Davis, 2016) and would perhaps require a more carefully controlled experiment (e.g., in a realistic performance setting with variable access to task-relevant information cues). The current findings do, at least, suggest that elite athletes depend on task-relevant information processing (Herrebrøden, 2023). This can make them prone to dual-task costs when attentional resources are (sufficiently) taxed by cognitive load.

Besides testing our hypotheses, we found several effects of physical load on rowing kinematics. Specifically, going from low to high physical load involved shorter stroke lengths, tighter coupling between leg and trunk motion during both drive and recovery, and reduced smoothness. This appears sensible since higher physical intensities tend to involve higher stroke rates, which is inversely related to stroke lengths (e.g., Hofmijster, Landman, Smith, & Knoek Van Soest, 2007; Soper & Hume, 2004). In turn, the rower has less time and space to develop power, explaining why the coupling between kinematic events is tighter. As mentioned, when discussing the cognitive load effects, these compressed actions should further cause more abrupt rowing strokes, explaining why rowers demonstrated less fluid handle motion during high physical load, since power must be developed over a shorter distance and time span. Yet, our manipulation check suggested that high physical load involved greater speed control, as evidenced by smaller speed variability, than low physical load. This may be partly due to the greater amount of feedback received by the rower when using a higher stroke rate, since the ergometer monitor provides stroke-by-stroke information regarding rowing speed, allowing the rower to adjust force for each stroke. It is also possible that smaller speed variability observed during higher stroke rates could be related to smaller timing variability commonly associated with shorter inter-onset intervals (e.g., Peters, 1989). Overall, the effects of physical load in the present study appear to make sense, given the current rowing task characteristics.

It is worth noting some potential limitations in the current study. The group sizes were determined by the number of rowers that were part of the highest-level training group of the Norwegian national team, resulting in a modest sample size. Further, when comparing the current performance conditions to a typical rowing race, our study lacked ecological validity. For one, there are biomechanical differences between ergometer rowing and on-water rowing (Kleshnev, 2005), and the latter is more complex (e.g., by having to deal with wind and waves). Second, the physical load in our study never approached maximal intensity. Since skill-level differences tend to become clearer with greater task demands (see, for example, Arsal, Eccles, & Ericsson, 2016), analyses of a competitive race might be needed to fully investigate rowing proficiency. Finally, it is worth entertaining the possibility that the kinematic changes in the dual-task conditions were due to some other factor than attentional capacity demands. For example, the presentation of arithmetic problems via speakers might have masked relevant auditory feedback (e.g., from the ergometer's fan), or the verbal responses may have interfered with the athlete's preferred breathing rhythm. However, we find these to be unlikely possibilities since both the problem presentations and verbal response durations were relatively brief. In sum, we believe that our study provided a robust test of cognitive load during a complex motor task, even though we encourage studies of even higher ecological validity in the future.

5. Conclusion

Complex motor task performance seems to require online attentional monitoring, even in elite athletes. A likely consequence of cognitive load or distraction, as observed in the current study, is that the motor performer frees up attentional capacity by reducing movement complexity. While this might be needed to attend to the distracting stimuli, attention to task-relevant cues appear key to achieving optimal motor performance. Hence, it appears that distractors may take important resources *away* from the motor performer's primary task (see Gray, 2020a). Thus, current findings are in line with distraction theories (see Christensen et al., 2015) and models advocating for cognitive control over skilled action (e.g., Christensen, Sutton, & McIlwain, 2016; Eysenck et al., 2007). Automaticity frameworks, on the other hand, find little support in our study. Specifically, the current findings do not provide support for the use of dual tasking to assess skill levels (cf. Gabbett et al., 2011) or train implicitly to promote better performance (cf. Maxwell, Masters, & Eves, 2000), especially when the cognitive load is high. Even though elite athletes make motor actions seem easy and effortless, it appears that they rely on cognitive resources.

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Declaration of interest

None.

CRediT authorship contribution statement

Henrik Herrebrøden: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Alexander Refsum Jensenius:** Conceptualization, Writing – review & editing, Supervision. **Thomas Espeseth:** Conceptualization, Writing – review & editing, Supervision. **Laura Bishop:** Conceptualization, Data curation, Writing – review & editing, Supervision. **Jonna Katariina Vuoskoski:** Conceptualization, Formal analysis, Writing – review & editing, Supervision.

Data availability

Data is available upon request.

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