Physiology & Behavior 239 (2021) 113490

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Effects of social support on performance outputs and perceived difficulty during physical exercise

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ARTICLE INFO

Keywords:
Social support
Exercise
Self-regulation
Placebo
Pain
Fatigue

ABSTRACT

Perceptions of social support influence adaptive self-regulatory processes that maintain health, produce feelings, and motivate behavior. Although associations between sociality and health are increasingly well-understood, there is little systematic research into the effects of social support on fatigue, physical discomfort, exertion, and output regulation in physical activity. We conducted an experimental study to investigate the effect of social support on performance and perceived difficulty in a handgrip force task while controlling for audience and reputational factors. Effects were compared with those of another established psychogenic performance enhancer (a placebo ergogenic supplement). During handgrip trials over varying levels of objective difficulty, participants viewed photographs of a support figure or stranger while in a placebo or control condition. Results revealed a significant main effect of the social support cue on handgrip performance outputs, and a significant interaction with objective trial difficulty – relative to the stranger cue, the support-figure cue significantly increased handgrip performance outputs and the effect was larger in more objectively difficult trials. Moreover, despite producing greater handgrip outputs, participants perceived trials to be significantly less difficult in the social support condition. Though there was a non-significant main effect of placebo (vs. control) on performance outputs, participants perceived trials in the placebo condition to be significantly less difficult. The research contributes new evidence and theory on the role of perceived social support – an important (energetic) resource – in human performance and motivates further enquiry into how cues to support alter perceived effort and performance outputs in strenuous physical challenges.

1. Introduction

Human behavior across evolution, ontogeny, and culture is characterized by high levels of social interdependence [1]. Cooperative social relationships are associated with greater access to fitness-relevant resources – the energetic, social, and cultural benefits of cooperation – while social isolation harbingers reduced access to resources and therefore lower fitness [2-4]. As a consequence, fitness-relevant homeostatic functions [5, 6], including buffering of pain and stress [7, 8] and regulation of emotion [e.g., 9], are functionally tied to social interaction, integration, and support.

In humans, as in many other species, complex whole-body regulatory systems function within and calibrate to internal and external environmental conditions of safety, opportunity, and threat [10]. Information about environmental conditions is processed via multiple sensory and cognitive mechanisms. Previous research has shown that adaptive self-regulatory processes are sensitive to perceptions of resources and social support availability, affecting outcomes from health to physical performance [11-13]. Perceived social support influences the adaptive processes that govern energetic resource allocation, protect homeostasis, produce feelings, and motivate behavior [6, 14-19].

Although there has been substantial progress in understanding the mechanisms and effects of perceived social support on homeostatic function and health, relevant advances across fields lack integration. For example, despite similarities in research domains, questions, and methods, research on clinical outcomes has traditionally proceeded separately from research on human performance (e.g., in endurance exercise) [12, 20, 21]. Likewise, studies on the effects of placebo treatments and social support interventions – both of which can be understood as influencing beliefs and expectations about resource availability

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https://doi.org/10.1016/j.physbeh.2021.113490
Received 8 February 2021; Received in revised form 30 May 2021; Accepted 31 May 2021
Available online 15 June 2021
0031-9384/

– have occupied distinct research areas. As a result, theoretical and empirical links across these phenomena have been largely ignored, while comparisons that reflect the specific concerns and intellectual traditions of each field have been systematically pursued (e.g., active treatment vs. placebo; social support vs. competitive rivalry).

We suggest that a biosocial, evolutionary framework unifies these disparate perspectives and motivates new questions. Here, we propose that cues of social support carry information about the potential availability of resources and, as such, influence adaptive self-regulation of energy allocation strategies across human activity, including physical activity and exercise performance [22].

Human sociality is defined by the interdependent exchange of fitness-relevant resources, from energy and information to safety and support [23]. Throughout human evolution, proximity to benevolent cooperative partners has typically been associated with greater potential access to resources (the benefits of cooperation) while social isolation has typically been associated with exclusion from these benefits. Perceptions of social support availability, much like perceptions and expectations about a purportedly efficacious clinical treatment or ergogenic aid, can significantly influence adaptive self-regulatory processes, such as pain perception and the stress response [24, 25]. Whether in the context of health or physical performance, these processes produce feelings, motivate behaviors, and maintain homeostasis [17, 26]. For example, support from a spouse in the form of hand-holding has been shown to reduce threat responses to potential electric shock, with those participants who felt closer to their spouse showing greater threat response attenuations [8]. Importantly, the effects of social support extend beyond direct social interactions. Even cues to socially supportive relationships can have analgesic effects; participants report nociceptive stimuli as less painful when viewing a photograph of their romantic partner, compared to when viewing a photograph of a stranger or object [27]. Neuroimaging research has shown that these analgesic effects are underpinned by reductions in pain-related neural activity and increased activity in brain areas associated with safety signaling [12].

In the context of physical exercise performance, feelings of fatigue and pain inhibit performance in part via sensations of exertion and difficulty [28, 29]. Evolutionary-psychophysiological models of physical exercise performance view these affective states not merely as an epiphenomenon of afferent feedback from peripheral systems, but as centrally-acting performance modifiers that adaptively and cautiously protect against risks associated with injury, overexertion, and exhaustion [29, 30]. Perceptions of fatigue, pain, exertion, and difficulty functionally integrate a range of conscious and unconscious perceptions and beliefs about safety and the current and future effort and resources needed for performance and recovery [30, 31]. These perceptions reflect the continuous, dynamic integration of bottom-up (peripheral) and top-down (central) feedback and, through their influence on performance behavior, adaptively regulate the conservation of a biological reserve [32, 33]. Central feedback incorporates a wide range of facilitative and inhibitory factors, including affective (e.g., positive emotion), motivational (e.g., goal incentives), and cognitive (e.g., expected exercise duration) elements [34-36]. Importantly, then, there is not a one-to-one relationship between the intensity of the peripheral signals and the felt sensations of fatigue and pain. A given energy expenditure and performance output can be associated with varied felt intensities of fatigue, pain, exertion, and difficulty according to (perceptions of) context. We suggest that an important but hitherto overlooked contextual factor is the availability of socially channeled energetic resources.

The impact of perceptions about resource availability, in general, on performance regulation during physical exercise is illustrated by mounting evidence for ergogenic placebo effects. Research on placebo effects has found that perceptions or expectations about having received an ergogenic aid can enhance performance outputs for a given (or reduced) level of perceived effort [37]. For example, an experimental study reported a mean increase in cycling performance of 3.1% and 1.3% following ingestion of a purported 'high' and 'moderate' dose of caffeine, respectively, despite administration of an identical placebo capsule in both conditions. In a third condition, in which participants were informed that they would receive a placebo, performance declined relative to baseline (−1.4%). Participants' qualitative statements suggest that the effects on performance were associated with perceived reductions in fatigue and pain (e.g., "it was easier to put the effort in", "I don't think there was so much pain") [38]. A recent systematic review of ergogenic placebo studies has identified similar effect sizes across other sport and exercise contexts [37].

The research on nutritional placebos suggests a potential role for resource-cues, including close attachment figures, in buffering sensations of fatigue and pain in physical exercise, and, ultimately, enhancing performance. Indeed, mechanistic studies suggest that the similarities between ergogenic placebo and perceived social support may be more than analogous. Neuroimaging and neuropharmacological blocking research has revealed that ergogenic placebo effects are underpinned by activity in endogenous pain modulation systems that are also associated with the analgesic effects of social reward and support [8, 12, 38-41]. For example, the endogenous opioid system is activated by cues to close social relationships [42-44] and has also been shown to underpin fatigue, pain, and exertion reductions associated with enhanced physical outputs in ergogenic placebo studies [40, 41, 45].

Here, we expand recent integrative psychophysiological models of fatigue and pain in physical exercise to examine the role of resource-relevant social cues on performance and perceptions of difficulty. We suggest that cues to safety and support potentially influence performance through calibrating sensations of fatigue, pain, exertion, and difficulty. In the context of exercise, we hypothesize that social support effectively lifts the 'brakes' on performance (i.e., sensations of fatigue, pain, exertion, and difficulty) that preserve reserve capacity and protect from overexertion and (further) injury [30, 32, 35]. When social cues suggest the availability of resources for performance or recovery, these safety mechanisms can be relaxed, ultimately leading to greater physical outputs for the same or reduced perceived fatigue, pain, exertion, and difficulty (all else, such as goal states, being equal).

Although receiving an ergogenic placebo has been shown to reduce fatigue and pain and enhance physical performance [40, 41], research has yet to establish a similar link between social-support-based reductions in pain and improvements in physical performance, and no studies have tested and compared their effects in a controlled experiment. Furthermore, no study has examined whether the strength of these effects varies with objective task difficulty. The adaptive self-regulation account proposed here suggests that available resources in the environment have greater salience and impact as the physical challenge faced by the individual, and therefore the resources required to complete (or recover from) the challenge successfully, increase. Understanding the effects of social support on individuals' experiences and outputs during physical exercise would inform observational findings associating socially supportive environments with positive outcomes in sport [16] and provide much-needed insights into the potential public health value of exercise in social settings [15, 46-48]. While social exercise settings, and social support more generally, have been linked to increased adherence to physical activity [49-51], less is understood about how social environments affect subjective experiences and the duration and/or intensity of outputs during physical activity [7, 52].

To test our hypothesis, we examined the effects of a cue of social support on performance and perceptions of difficulty in a handgrip exercise task, and compared effects to those of a (placebo) performance-enhancing supplement. The task design allowed us to control target outputs (i.e., by varying objective exercise difficulty) across conditions and the novel experimental paradigm is also compatible with neuroimaging technologies (e.g., to investigate potential shared neurobiological pathways between placebo and social support effects [53, 54]). Participants' perceptions of social support during the handgrip trials were manipulated by making visible a photograph of either a stranger (control condition) or someone they viewed as supportive in their life (support condition) [12]. To manipulate beliefs about being under the influence of an ergogenic supplement, participants were given a placebo 'performance-enhancing' pill before one of two handgrip exercise blocks [38, 40].

2. Hypotheses

Hypothesis 1a and Hypothesis 1b: handgrip outputs in the social support (H1a) and placebo (H1b) conditions will be higher than in their respective control conditions.

Hypothesis 2a and Hypothesis 2b: objective trial difficulty will moderate the ergogenic effects of social support (H2a) and placebo (H2b) on handgrip outputs, such that effects will increase with objective handgrip trial difficulty. This will be evidenced by significant social support × objective trial difficulty and placebo × objective trial difficulty interactions on handgrip outputs.

Hypothesis 3a and Hypothesis 3b: for a given performance output, perceived difficulty in the social support (H3a) and placebo (H3b) conditions will be lower than in their respective control conditions. Our measure of perceived difficulty captures the psychological components of fatigue, pain, and exertion in (goal-directed) endurance performance [29], which, as described above, are primary determinants of outputs during physical exercise [30]. Greater performance outputs at equivalent or lower perceived difficulty in the support condition compared to the control condition would support our account that sensations of fatigue and pain are adaptively calibrated to perceived socio-environmental conditions (i.e., the "brake" is lifted vs. lowered in the presence vs. absence of support).

Hypothesis 4: social support effects on handgrip outputs will be predicted by individual factors related to how social support is received. Specifically, previous research has shown that neurotic individuals are less likely to benefit from social support [52, 55], and that social support effects are strongest in those who need social assurance from others [56], in those who depend on others to be available when needed [57], and when received from someone with whom the suportee has a quality relationship [8]. Thus, neuroticism was hypothesized to have a negative relationship with social support effects, while need for social assurance, ability to depend on others, and relationship quality with the support figure seen in the social support condition were all hypothesized to have a positive relationship with social support effects.

3. Methods

3.1. Power analysis

A power analysis for multilevel linear models generated a recruitment goal of 80 participants [58]. The power analysis assumed small effect sizes in the placebo and social support conditions (d = 0.1), derived from previous ergogenic placebo studies [37, 59]. Power was set to 0.8, an alpha level of 0.05 was used, and random variance proportions were set to 0.8 for the residual, 0.19 for the intercept, and 0.005 for each of the fixed effects in the proposed model with random slopes (placebo and social support fixed effects) [58, 60].

3.2. Participant recruitment

Participants were recruited from Oxford, UK. Participants were required to be aged 18 – 49. The age requirement was used to recruit from the general population a participant sample with an age distribution similar to those used in previous relevant social support and placebo research [12, 33], and to reduce age-related variation in study measures (which was not of theoretical interest). Participants were also required to confirm (via self-report) that they (a) were able to sustain moderate intensity exercise ("e.g., brisk walk or easy jogging") for a minimum of 30 min, (b) had refrained from doing strenuous physical exercise or using illegal drugs and alcohol in the 12 hr period preceding their participation in the study, and (c) were free of any prior or current conditions or injuries that would have prevented them from safely completing the handgrip exercises. Prior to the experiment, participants were asked to submit a passport-style photograph (smiles allowed) of "someone you feel you have a close connection with and that you can depend on in times of need – such as a friend, family member, or partner".

After excluding seven participants due to equipment malfunction and six participants for failure to follow experimental instructions (see SOM 1 for full details), a total of 72 participants were included in analyses (41 females, age range = 18 – 40 years, M = 23.90 years, SD = 4.49 years). Although the number of participants with usable data was below the recruitment goal of 80 set by the initial power analysis, a total of 72 participants gave the study an acceptable estimated power of 0.75 (holding constant all other variables from the initial power analysis).

All participants gave informed consent and were remunerated £30 GBP. This study was approved by the Medical Sciences Inter-Divisional Research Ethics Committee, University of Oxford (reference number: R47623/RE001).

3.3. Experimental procedures

3.3.1. Participant introduction to the experiment

Upon arrival at the study venue (John Radcliffe Hospital, Oxford, UK), participants read an information sheet on the "performance-enhancing drug", beta-alanine (β-alanine), and were informed that they would receive the drug before one of the handgrip exercise blocks [38]. Participants were then introduced to the experimental task and equipment, after which they consented to take part in the study. Following this, participants' maximum handgrip strength was assessed; each participant's maximum handgrip strength was used to calibrate the objective handgrip trial difficulty levels. Next, to increase participants' beliefs about the efficacy and legitimacy of the β-alanine treatment, each participant was weighed and asked to disclose any medication they were taking. The experimenter then left the room for 5 min (putatively to retrieve the weight-adjusted dose of β-alanine from a pharmacist) before returning to begin the experiment (see SOM 2, SOM Figure 1, SOM Figure 2, and SOM Table 1 for details of experiment instructions and the information and consent forms).

3.3.2. Pre-exercise questions

To ensure participants met recruitment criteria, they were first asked whether they had taken any drugs or performed strenuous exercise in the past 12 hr. They were then asked their age and sex, and whether they had heard of β-alanine in relation to performance enhancement during exercise.

Participants then answered pre-validated measures on their personality traits and relationship styles. The 44-item Big Five Inventory [61] was used to assess neuroticism. The "depend" subscale of the close relationship version of the Revised Adult Attachment Scale (e.g., "I find that people are never there when you need them.") was used to assess the degree to which participants depend on others to be available when needed [57].

To prime participants' thoughts about exercise-induced discomfort, they were asked to complete a modified version of the short form of the Fear of Pain Questionnaire [62], to which a question about "having muscle cramps" was added. To evoke strong sentiments about support figures (the person depicted in the previously submitted photograph) before the exercise portion of the study, participants were asked to describe an instance of feeling either close to or supported by their support figure. See SOM 3 for detailed formats of all pre-exercise questions. See SOM 4 for examples of participants' descriptions of feeling either close to or supported by their support figure.

3.3.3. Handgrip exercise

The handgrip exercises were administered in two blocks (see Fig. 1)

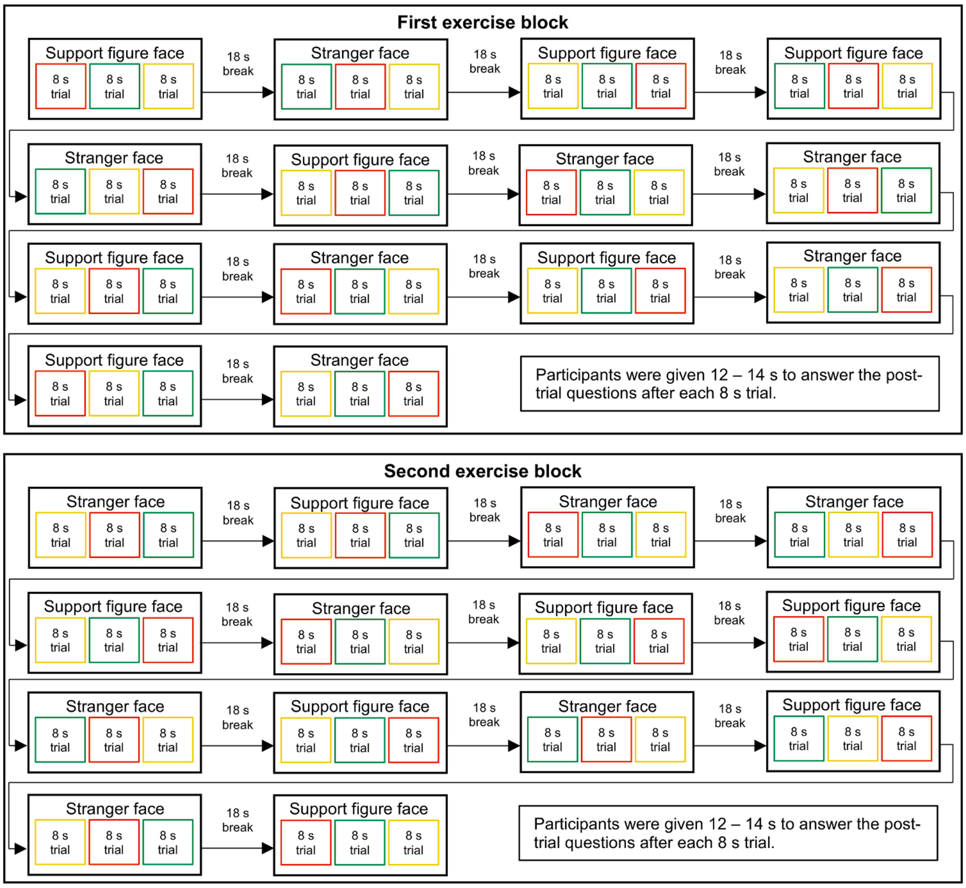

Fig. 1. A schematic depiction of the experimental design; green, yellow, and red squares represent trials with target handgrip strengths of 40%, 50%, and 60% of participants' maxima, respectively. Participants took the placebo before either the first exercise block or the second exercise block, in a randomized, counterbalanced fashion. For each exercise block, the order of target trial difficulty and of the faces (support figure or stranger) seen during the handgrip exercise trials was randomized and counterbalanced, as shown here.

using a 3-D printed, fMRI-compatible hand grip [53]. Handgrip force was measured using a fiber-optic sensor, which was housed inside the hand grip. This sensor captured internal, grip-force-dependent displacements within the hand grip; these displacements were used to quantify participants' handgrip strengths during the handgrip exercises [53].

There were two main blocks of exercise; within each block (duration approx. 22 min), there were 14 sub-blocks consisting of three, 8 s handgrip trials. Each block of three trials involved sustained isometric contraction of the hand grip at a target difficulty of either 40%, 50%, or 60% of the participant's maximum handgrip strength (one trial at each difficulty level per sub-block, in randomized order; see Fig. 1).

Participants were seated in front of a 27-inch monitor that displayed the handgrip exercise stimuli. In each sub-block, participants viewed an image of the face of their support figure or an image of the face of a stranger during the 8 s hand grip trials – the social support manipulation (for details, see 3.3.4 and SOM 5). During the 8 s trials, a horizontal line on the screen (superimposed over the support figure or stranger image) moved up or down an invisible vertical axis according to the participant's handgrip strength – the harder they squeezed, the higher the line rose (see Fig. 2).

The exercise task goal was to raise the line above the target bar (set at either 40%, 50%, or 60% of the participant's maximum handgrip strength), turning it from red to green, and to keep the line above the target bar for the duration of the 8 s trial. Regardless of trial target difficulty level, the target bar remained stationary and was always in the same place on the screen. Handgrip strength was measured 20 times per second over each 8 s trial. All data points were included as the outcome variable in the multilevel model used to analyze the effects of the experimental manipulations on participant handgrip outputs.

3.3.4. Social support manipulation

Participants viewed the photographic image of the face of the support figure that they had submitted ("support" condition) or the face of a stranger ("stranger" condition), matched to the support figure on gender, age, ethnicity, and the degree to which the support figure was

Fig. 2. The handgrip exercise interface when the participant is contracting at 0% of their maximum (left) and above their target handgrip strength of either 40%, 50%, or 60% of their maximum (right). Trial target handgrip strength is represented by the stationary white line superimposed on a photograph of the participant's support figure or a stranger; actual handgrip strength is a vertically moving line that is either red (below the trial target handgrip strength), green (on or above the trial target handgrip strength), or yellow (shown on completion of the 8 s trial).

smiling (see Fig. 2 for photograph presentation and SOM 5 for details on photograph processing and acquisition). Images were displayed on the screen and in a randomized order across the 14 sub-blocks of each exercise block (see Fig. 1).

3.3.5. Placebo manipulation

In a counterbalanced fashion, participants received what they were told was a β-alanine capsule either before the first or second exercise block (each block corresponded to either the "placebo" or "control" condition). The capsule was actually a placebo; 430 mg of sucrose, given to participants in a "black baggie" with a pharmacist's label that included the experiment date along with the participant's name and a coded weight category (see SOM Figure 3 for an example of the placebo presentation). To allow participants to recover between exercise blocks, and consistent with the advice that they had actually taken β-alanine (the putative effects of which were said to last 45 min, after taking 20 min to take hold), each exercise block was preceded by a 30 min break during which participants performed an unrelated memory task.

3.3.6. Post-trial questions

After each trial, participants answered two questions in the following order: "How hard was it to keep the bar above the line?" (perceived difficulty measure) and "How much effort did you put in to keep the bar above the line? (perceived effort measure). Piloting suggested that participants better understood exercise difficulty induced by fatigue and pain in terms of "how hard it was" to complete the exercise task; this term (which also anchors the upper range of the Borg Rating of Perceived Exertion scale [63]) was thus used. The perceived effort item was included as a measure of participants' engagement with the task, or motivation, and was included as a covariate in analyses. Answers were given on a sliding scale (0 = *not hard at all*, 100 = *extremely hard*, and 0 = *no effort at all*, 100 = *maximum effort*). As the questions remained unchanged after each 8 s trial, participants were given 5 s to answer each question. After each sub-block, participants saw a blank, black screen for 18 s.

3.3.7. Post-exercise questions

After completing all trials, participants answered a series of questions that were used to confirm the effectiveness of the social support and placebo manipulations. Regarding the social support manipulation, participants rated, using 5-point Likert scales (1 = *Strongly disagree*, 5 = *Strongly agree*), how much they agreed with the statements "I felt close to my friend, family member, or partner when I saw their photo during the exercise trials." and "I felt close to the other person whose photo I saw during the exercise trials." Regarding the placebo manipulation,

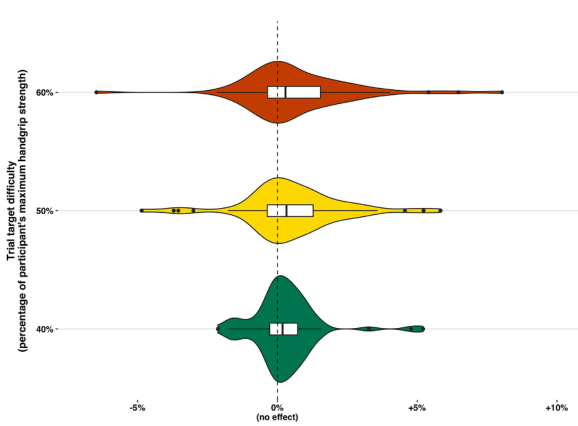

Fig. 3. Mean effect of social support (viewing a photograph of a support figure) versus its control (viewing a photograph of a stranger face) on handgrip outputs for each participant at each trial target difficulty (percentage of participant's maximum handgrip strength).

participants reported, using 100-point sliding scales, the extent to which β-alanine had a positive or negative effect on their performance (0 = *Strong negative effect*, 100 = *Strong positive effect*), and the degree to which it made the exercise trials easier or harder (0 = *It made them easier*, 100 = *It made them harder*).

A series of measures were used to test whether individual personality factors and relationship strength and needs predicted social support effects. First, participants completed the Social Assurance Scale, a measure pre-validated with undergraduate students from the United States and used to assess participants' need for assurance from others (e.g., "I feel more comfortable when someone is constantly with me.") [56]. Following this, they rated, using a 7-point Likert scale, the extent to which their support figure was "someone you feel you have a close connection with and that you can depend on in times of need" (1 = *Not at all*, 7 = *Very much*). This description was derived from standard definitions of perceived social support in the literature [6, 13]. Participants then reported how long they had known their support figure in this way.

Finally, participants responded to a hypothesis probe. See SOM 6 for detailed post-exercise question formats.

3.4. Statistical models

All analyses were conducted in R version 3.5.3. Multilevel linear regression was used to analyze handgrip outputs, with participants comprising the level-two random factor [64-66]. Due to ceiling effects in the data (see SOM Figure 4), a multilevel censored regression model was used to analyze perceptions of difficulty, with participants again comprising the level-two random factor [67, 68]. Linear regression models were used to test whether personality or relationship characteristics predicted social support effects.

We used z-tests on estimated marginal means for post hoc analyses of significant interactions estimated using multilevel linear models [69], and t-tests on group means for post hoc analyses of significant interactions estimated using multilevel censored regression models (currently, there are no methods in R for carrying out post hoc analyses directly on multilevel censored regression model estimates) [68].

Sum contrasts (also known as deviation coding) were used for all binary predictor variables in these models; the social support, placebo, and exercise block (first and second) variables. This variable coding system causes linear models to compare the mean of the outcome variable at a reference condition of the predictor variable (here, the social support, placebo, and second exercise block conditions) to the overall mean of the outcome variable across all conditions. 'Main effects' were thus calculated by multiplying model b coefficient estimates by two, which gives the estimated difference between the two experimental conditions represented by the binary variable [70]. All other model predictor variables were scaled (and mean centered at 0) to improve the likelihood of model convergence and facilitate model interpretation [60].

When modeling the main outcome variables (handgrip outputs and perceptions of difficulty), the experiment has a 2 (social support condition) × 2 (placebo condition) × 3 (trial target handgrip strength) × 2 (exercise block) design, creating the potential for three and four-way interactions in the statistical models. To facilitate model fit and interpretation, it is recommended that multilevel models are specified as parsimoniously as possible (e.g., minimizing complex interactions and random effects structures) [60]. The exercise block variable is an artefact of counterbalancing the placebo condition and not of theoretical interest. This variable was therefore dropped as a model interaction term when it did not interact significantly with the predictor variables of interest (i.e., the social support and placebo variables). The three-way social support condition × placebo condition × trial target handgrip strength (henceforth, trial target difficulty) interaction was also not of theoretical interest, and dropped when not statistically significant.

As a result, with participants' handgrip outputs as the outcome variable, the exercise block variable was dropped as an interaction term, as it did not significantly interact with the social support variable, $b = -0.02$, SE = 0.02, $t = -1.54$, $p = .123$, or the placebo variable, $b = 0.82$, SE = 0.73, $t = 1.12$, $p = .265$. The non-significant three-way social support × placebo × trial target difficulty interaction was also dropped, $b = 0.02$, SE = 0.02, $t = 1.32$, $p = .188$ (see SOM Table 2 for full model results). The final model on participants' handgrip outputs therefore contained only the three two-way interactions between the social support variable, the placebo variable, and the trial target difficulty. The model included as covariates participants' reported effort levels (to control for motivation) and the exercise sub-block number. Exercise block was also retained as a covariate as it improved model fit. The maximal random effects structure that also allowed for model convergence was used [71]; in this case, random effects for the placebo condition only.

In analyses on perceptions of difficulty as the outcome variable, the placebo × exercise block interaction was significant, $b = 4.00$, $SE = 0.18$, $t = 22.69$, $p < .001$ (see SOM Table 3 for full model results). The 2 × 2 × 2 × 3 design was thus retained for the final model analyzing the effects of social support and placebo on participants' perceptions of difficulty. This model again included participants' reported effort levels and the exercise sub-block number as covariates. Multilevel censored regression models in R allow only for random intercepts [68].

4. Results

4.1. Manipulation checks

One-sample *t*-tests against scale midpoints revealed that participants felt that β-alanine had a positive effect on their exercise performance, $t(71) = 5.53$, $p < .001$, and that it made the exercise trials easier, $t(71) = 3.83$, $p < .001$. They also reported feeling closer to their support figure than to the stranger, $W = 1{,}907.5$, $p < .001$. For full statistics on manipulation checks and other relevant variables, see SOM 7 and SOM Table 4.

Participants were, on average, able to meet and sustain the trial target handgrip strengths at all objective difficulty levels (see SOM Figure 5 and SOM Table 5). Perceptions of difficulty increased as trial target difficulty increased from 40% ($M = 55.23$, $SD = 23.14$) to 50% ($M = 70.18$, $SD = 21.23$) to 60% ($M = 82.55$, $SD = 18.38$) of participants' maximum handgrip strength (see SOM Table 6). Reported effort levels also increased as trial target difficulty increased from 40% ($M = 59.55$, $SD = 24.04$) to 50% ($M = 72.32$, $SD = 20.80$) to 60% ($M = 82.31$, $SD = 18.16$) of participants' maximum handgrip strength (see SOM Table 7). See SOM 8, SOM Figure 6, and SOM Figure 7 for full descriptive statistics on handgrip outputs, perceptions of difficulty, and reported effort levels.

4.2. Social support and placebo effects on handgrip outputs (Hypothesis 1a and hypothesis 1b)

There was a significant main effect of social support on handgrip outputs (H1a); participants had significantly higher handgrip outputs when viewing their support figure face than when viewing the stranger face, $b = 0.40$, $SE = 0.02$, $t = 12.94$, $p < .001$, 95% CI: [0.34, 0.46] (see Fig. 3). There was a non-significant main effect of placebo on handgrip outputs (H1b) and a non-significant social support × placebo interaction on handgrip outputs. See SOM Table 8 for full model results.

4.3. Moderation of social support and placebo effects on handgrip outputs by objective trial difficulty (Hypothesis 2a and hypothesis 2b)

There was a significant social support × trial target difficulty interaction on handgrip outputs (H2a), $b = 0.10$, $SE = 0.02$, $t = 5.42$, $p < .001$, 95% CI: [0.07, 0.14] (see Fig. 3). The interaction between placebo and trial target difficulty was not significant (H2b), $b < 0.01$, $SE = 0.02$, $t = -0.05$, $p = .965$. See SOM Table 8 for full model results.

Post hoc analyses of the social support × trial target difficulty interaction (with Bonferroni-corrected α values) revealed that the performance-enhancing effects of social support on handgrip outputs increased with objective trial target difficulty (see Fig. 3). Significant differences in handgrip outputs between the social support and control (stranger) conditions were revealed for trials with handgrip strength targets at 50% ($b = 0.51$, $SE = 0.15$, $Z = 3.40$, $p < .001$, 95% CI: [0.22, 0.80]) and 60% ($b = 0.66$, $SE = 0.15$, $Z = 4.36$, $p < .001$, 95% CI: [0.36, 0.95]), but not at 40% ($b = 0.25$, $SE = 0.15$, $Z = 1.68$, $p = .092$), of participants' maxima (see SOM Table 9).

4.4. Social support and placebo effects on perceived difficulty (Hypothesis 3a and hypothesis 3b)

There were significant main effects of social support (H3a), $b = -1.53$, $SE = 0.23$, $t = -3.36$, $p < .001$, 95% CI: [−2.49, −0.65], and placebo (H3b), $b = -0.54$, $SE = 0.16$, $t = -3.42$, $p < .001$, 95% CI: [−0.85, −0.23], on perceived difficulty. Participants perceived handgrip trials in the social support and placebo conditions to be significantly less difficult than in the respective control conditions. There was also a significant placebo condition × exercise block interaction, $b = 5.89$, $SE = 0.25$, $t = 23.36$, $p < .001$, 95% CI: [5.64, 6.38]. For full model results, see SOM Table 3.

Post-hoc analyses revealed a significant difference in perceptions of difficulty between the control and placebo conditions in the second exercise block, but not in the first. Exercise trials in the second exercise block were perceived as significantly less difficult by participants who received the placebo before this block, compared to those who did not receive the placebo before this block ($M_{\text{difference}} = -3.15$, $t = -3.54$, $p < .001$, 95% CI: [−4.90, −1.40]). Differences in perceptions of difficulty were not statistically significant between the participants who received the placebo before the first exercise block and those that did not ($M_{\text{difference}} = -0.90$, $t = -1.08$, $p = .282$, 95% CI: [−2.54, 0.74]; see SOM Table 10). Fig. 4 shows the main effect of placebo on perceived difficulty, as well as its interaction with exercise block. Across both exercise blocks, perceived difficulty is lower in the placebo condition, but the difference between the control and placebo conditions is larger in the second exercise block.

Crucially, lower ratings of perceived difficulty were not associated with lower handgrip outputs. Participants perceived exercise trials in the social support condition to be significantly less difficult while also

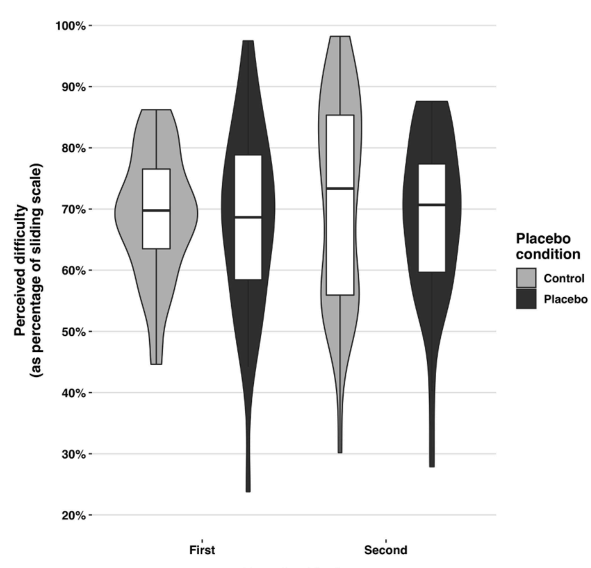

Fig. 4. Mean perception of handgrip trial difficulty for each participant, by exercise block and placebo condition. Perceptions of difficulty were given as a percentage of the sliding scale used, where 0% was "not hard at all" and 100% was "extremely hard".

producing significantly higher handgrip outputs. Participants perceived exercise trials in the placebo condition to be significantly less difficult while producing statistically similar handgrip outputs; the interaction between placebo and exercise block on handgrip outputs was not significant. See SOM 8 and SOM Table 5, SOM Table 6, and SOM Table 9 for summary statistics for handgrip outputs and perceived difficulty by experimental condition.

4.5. Predictors of social support effects on handgrip outputs (Hypothesis 4)

Of the variables hypothesized to relate to the strength and direction of social support effects (participants' neuroticism, need for social assurance, ability to depend on others, and the quality of their relationship with their support figure) none significantly predicted the observed social support effects on handgrip outputs (see SOM 9 and SOM Table 11 – SOM Table 14).

4.6. Model diagnostics

For model diagnostics – assumption checks and outlier influence tests – of all models with significant findings, see SOM 10.

5. Discussion

This study investigated social support and placebo effects on performance during a challenging handgrip exercise. Results revealed that social support had a positive (ergogenic) effect on handgrip outputs (Hypothesis 1a), and that the positive effect of social support increased along with the objective difficulty of the exercise (Hypothesis 2a). Crucially, social support effects on handgrip outputs were statistically significant while controlling for participants' reported effort levels, suggesting that observed effects were not caused by differences in motivation. Moreover, increased handgrip outputs in the social support condition were accompanied by significantly lower levels of perceived difficulty (Hypothesis 3a).

There was no effect of placebo (Hypothesis 1b) or its interaction with objective exercise difficulty (Hypothesis 2b) on handgrip outputs. This may be due in part to the high inter-individual variability in response to the placebo treatment (see the standard error of the placebo *b*-coefficient in SOM Table 8). However, the placebo condition was associated with significantly lower levels of perceived difficulty relative to its control condition (Hypothesis 3b) and this effect was strongest in the second exercise block. Perceived difficulty ratings following the withdrawal of the purported β-alanine suggest a possible nocebo effect: the placebo × exercise block interaction was driven by participants who received the placebo in the first exercise block but who were led to believe that it had worn off by the second exercise block [21, 72].

Overall, the findings support our hypotheses and are similar to those previously reported on social environments and ergogenic placebos in exercise, albeit with some differences in the task demands (e.g., fixed threshold vs. maximum effort) [38, 59, 73]. The results offer further support for the hypothesized involvement of centrally mediated regulation of fatigue and pain in exercise performance [39, 41]. Physical outputs are attenuated in response to afferent fatigue and pain signals from peripheral muscles, but also to a range of other factors (e.g., goal states), protecting bodily resources and homeostasis under a particular set of conditions [30, 35]. Although social factors of competition and rivalry have been studied within this paradigm, perceived social support has been largely overlooked [74]. We suggest that cues to social support signal safety and protection and can function as an allostatic buffer, leading to top-down reductions in fatigue and pain perception. All else being equal, as the challenge intensifies, so too do the salience, value, and impact of available resources and support. This social buffering account is consistent with the results of the current study, in which increased social support effects on handgrip outputs were observed under conditions that were objectively and subjectively more difficult.

The observed effects of social support on handgrip outputs corroborate and potentially extend previous observational research linking socially supportive environments with improved adherence to and performance in physical exercise [16, 75, 76]. Previous research on social support effects has focused on outcomes in team and/or skill-based sports (e.g., wins and losses, putting in golf) or on metrics such as exercise class attendance [49, 77, 78]. Our study extends this research, providing a theoretical and empirical basis for the idea that social support can affect outcomes in exercise performance by reducing perceptions of difficulty and raising physical outputs.

Our theoretical approach provides an evolutionary account of why social environments affect psychophysiological states in social species [79], and proposes a potential mechanistic account of how social cues could affect physical outputs. Given high levels of social interdependence throughout human evolution [2], the presence of social support potentially signals safety and increased availability of energetic resources required for homeostatic maintenance, survival, reproduction, and growth. In the context of physical activity, cues to social support can lead to less cautious conservation of endogenous energetic resources, and therefore greater outputs. This integrative evolutionary approach situates the study of fatigue, pain, and performance squarely within a social and cooperative context, in contrast to the traditional individualistic-competitive emphasis that dominates the sports and exercise sciences. Research methods and evidence from across the social, cognitive, and clinical sciences can help to elucidate the mechanistic pathways underpinning the observed effects of perceived social support on perceptions of difficulty and performance. Social and clinical neuroscientific evidence suggests that, in the context of experimentally induced pain, cues to social support can act as a safety signal, reducing threat responses and perceptions of physical discomfort [8, 12, 27]. The current study extends this research by showing that a similar social support cue (a photograph of a support figure) has similar effects on perceptions of difficulty – which correlate with fatigue and pain signaling and perception [39, 80] – in the context of physical exercise.

Evidence suggests that the adaptive self-regulatory processes that maintain homeostasis in exercise, typically felt as fatigue and pain, are cautious by default, limiting physical outputs in individuals who still have considerable reserve capacity [e.g., in cardiac and muscle function; see 30]. Psychological states, such as the perceived presence vs. absence of resources relevant for performance and recovery or goal stakes of maintaining a higher output (e.g., escaping a predator, winning an Olympic Gold), can also adaptively calibrate the system to be less cautious, limiting performance via fatigue and pain only at relatively higher levels of physical effort [30]. We suggest social support acted as a tacit cue of safety and resource availability, lowering participants' perceived difficulty of the exercise trials by decreasing sensations (or "alarms") of fatigue and pain, which ultimately allowed for greater physical outputs in the social support condition.

The social support effects in this study could be interpreted from different, although not necessarily incompatible, theoretical perspectives. Previous research suggests that perceptions of belonging in a social group can act as a psychological resource that contributes to resilience during stressful or challenging events [81]. Specifically, this research has also shown an association between group membership and attenuated pain and stress responses. Those belonging to a greater number of social groups have been shown to have faster heart rate recoveries following a stressful event [82]. Prompting participants to reflect upon group memberships has been shown to increase persistence in skill-based sensorimotor tasks (golf putting) after negative feedback [83], and to increase pain endurance during a cold-pressor task [82]. These associations between group membership and psychological resilience are compatible with our broad theoretical approach, in which group membership can be a cue of safety and resource availability, thereby potentially altering psychological and related physiological states in the face of challenges and threats. Further research is needed to explore effects and psychophysiological pathways across a range of social support cues and performance contexts. Multidisciplinary theoretical advances in the study of "effort-related decision making" offer new promise for a unified approach to performance across traditionally disparate clinical, exercise, and cognitive-psychological domains [84].

In addition to elucidating ergogenic social support effects in individual tasks, the account proposed here potentially gives a material basis for the well-documented bonding-performance link in team sports [16] and for the impact of perceived social support on exercise adherence, wellbeing, and health more generally [6, 49]. This study's hypotheses and results can offer a novel perspective on the public health value of exercise in social settings (including community-based physical activity events and interventions [47, 48, 85]), supplementing existing research on exercise participation and adherence [15, 49, 50, 76]. That social support offers similar ergogenic effects to placebo could also have relevance for understanding the ergogenic effects of suggestion, positive expectation, and emotion regulation in exercise [86-88]. Evidence for ergogenic social support effects is also likely to be relevant to anti-doping research, which has focused on the effects of placebo treatments on athletes' performance [89, 90]; social support may offer another 'clean' route to performance-enhancement.

However, much more research on ergogenic social support effects is needed, including on underlying psychophysiological mechanisms. This study provides a novel design that could be used by future researchers to investigate potential overlap in the self-regulatory, neurobiological mechanisms that underpin ergogenic social support and placebo effects (e.g., the endogenous opioid and endocannabinoid systems [40, 41]).

5.1. Limitations and future research

This study offers novel insight into the relationships among social support, self-regulation, and experiences and outputs during physical exercise. Although results potentially inform several disparate bodies of research, this work can be seen as an initial proof of concept, and the study has several limitations that can motivate further enquiry. In particular, future research should aim to better understand the neurobiological mechanisms through which social support affects individuals' experiences and outputs during physical exertion in both laboratory and real-world settings. In this study, endogenous fatigue and pain modulation via activity in relevant neurobiological systems can only be inferred from participants' physical outputs and self-reports of perceived difficulty. Future research could aim to investigate and compare the neurobiological mechanisms underpinning the observed social support and placebo effects. Previous neuroimaging and pharmacological blocking studies have shown, for example, that both fatigue and pain correlate with activity in the endogenous opioidergic and endocannabinoid systems [12, 40], and that endogenous opioid activity is linked with ergogenic placebo effects [41]. This study's design allows for these systems to be studied in the context of social support and placebo effects in exercise performance; its design and equipment are fMRI-compatible, and could also be used with pharmacological blocking methods [e.g., 44].

Follow-up studies could also employ different methodologies to strengthen the experimental manipulations and further investigate interactions between ergogenic placebo treatments, social support, and participant motivations. Previous research has shown that conditioning procedures produce stronger analgesic and ergogenic placebo responses than suggestion alone [21, 40, 45]; the effect of the placebo manipulation used in this study may have been stronger if it had followed pre-experiment conditioning trials (e.g., where exercise difficulty is surreptitiously reduced after placebo β-alanine treatment).

Future work could also investigate how different types of social support affect outputs and experiences during physical exercise – the manipulation in this study was based on previous designs that cued emotional support, but other types of social support, such as instrumental or esteem support, may produce different effects [6, 91]. Participant motivation could be further manipulated to understand how different goal states interact with social support and ergogenic placebo treatments. Greater incentives and rewards likely alter the adaptive cost-benefit analyses that calibrate self-regulation in physical activity [29]. As (fitness-relevant) incentives and rewards increase, such as tracking prey or gaining reputational kudos, there may be diminished benefit to maintaining substantial reserve capacity.

Follow-up work could also distinguish among effects on perceptions of fatigue, pain, and perceived difficulty, and employ experimental designs that allow for dynamic measurement during, rather than after, exercise trials [86]. These designs should consider measures of fatigue, pain, and perceived difficulty that are less susceptable to ceiling effects. In this study, the modal answer to the post-trial question on perceived difficulty was at the extreme ('extremely hard') of the sliding scale used (see SOM Figure 4). A measure that allows for more variation in participant responses could better quantify experimental effects and allow for more nuanced statistical analyses. For example, the ceiling effect in this study's perceived difficulty measure ruled out the possibility of a follow-up causal mediation analysis that could have tested whether perceptions of difficulty mediated the positive relationship between social support and handgrip outputs. Current multilevel causal mediation analysis methods in R cannot accommodate the multilevel censored regression models needed to analyze outcome measures with ceiling effects [92].

Finally, this study used a 'lab-based' form of physical exertion (the handgrip exercise) as the primary outcome measure. Although the experimental design enabled a controlled manipulation of the social support and placebo treatments, and offers a paradigm that can be adapted to investigate underlying neurobiological mechanisms, the ergogenic effects of social support need to be tested in a wider range of performance contexts and behaviors (e.g., sport, occupational physical activity).

5.2. Conclusion

The novel findings of this study suggest that a cue of social support can affect experiences and outputs during physical exercise by altering activity in mechanisms involved in homeostatic self-regulation. The biosocial, evolutionary perspective on self-regulation during exercise performance presented here motivates further research to elucidate neurobiological mechanisms and socio-psychological factors that influence adaptive responses to perceived energetic demands and resource availability in contexts ranging from everyday physical activity and high-level competitive sport to wellbeing and health.

Funding

A Clarendon Scholarship to AD and John Fell Fund [number 153/065] award to EC and BC funded this research.

Data availability

The data and analysis scripts associated with this research are available at https://github.com/arranjdavis/experiment_on_social_support_and_placebo_effects_during_exercise.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

We thank Prof. Ulrike Bingel for her input to the study design, Dr. Hristo Hristov for his help with data analysis, and Kiah Rutz for her help with manuscript revision.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.physbeh.2021.113490.

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