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ORIGINAL ARTICLE

Preferred, but not objective temperature predicts working memory depletion

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Abstract The present study investigated the relationship between objective temperature and subjective temperature preferences in predicting performance in simple and complex cognitive tasks. We assessed the impact of room temperature (warm and cold) on the ability to "update" (and monitor) working memory (WM) representations in two groups of participants, who differed in their subjective temperature preferences (warm-preferred vs. cold-preferred). Participants performed an N-back task in which conditions (1-back and 2-back) differ in their WM load and cognitive demands. Results showed that the preferred, but not the objective temperature predicts WM performance in the more resource-demanding (the 2-back) condition. We propose that subjective preferences are more reliable predictors of performance than objective temperature and that performing under the preferred temperature may counteract "ego-depletion" (i.e., reduced self-control after an exhausting cognitive task) when substantial cognitive control is required. Our findings do not only favor a cognitive approach over the environmental/physical approaches dominating the research on cognition–environment interactions, but they also have important, straightforward practical implications for the design of workplaces.

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Introduction

Humans are strongly affected by climate and temperature, and many countries have guidelines establishing permissible temperature ranges at the working place. Experimental evidence suggests that room temperature can affect social behavior (IJzerman & Semin, 2009; Kang, Williams, Clark, Gray, & Bargh, 2011) and general well-being (see Hancock, Ross, & Szalma, 2007, for a review). Nevertheless, which cognitive operations are mediating such temperature-induced effects is unknown.

The few available studies investigating the effect of the exposure to moderately warm and cold temperatures suggest two conclusions: Warm temperatures seem to affect cognitive performance more strongly than cold temperatures do (Hancock & Vasmatzidis, 2003), and more complex tasks are more affected than simple tasks are (Cheema & Patrick, 2012; Hancock et al., 2007). This pattern fits with the general assumptions that the human body has greater tolerance for the cold than for the heat (Hammel, 1968) and that warmer temperatures tax human resources more than colder temperatures do (Hancock, 1986; Hancock & Vasmatzidis, 2003).

Considering this pattern, it can be assumed that warmer temperatures lead to greater and/or faster ego-depletion (cf. Baumeister, Bratslavsky, Muraven, & Tice, 1998). According to the ego-depletion account, only a limited pool of cognitive resources are available for rapidly depleting cognitive control operations, so that subsequent performance suffers from resource-depleting activities, and it does so the more demanding these activities were. If we assume that being exposed to warmer temperatures depletes more cognitive resources than being exposed to colder temperatures, warmer temperatures should leave fewer resources for cognitive tasks, which would be particularly visible in more complex tasks. Hence, the observed decrements in complex tasks performed in warmer environments (Hancock & Vasmatzidis, 2003) might result from ego-depletion.

The present study was motivated by informal observations suggesting that people differ with respect to the temperature they prefer to work in. On the one hand, such preferences might have little to do with the actual performance, which would suggest that objective temperature measures are more reliable performance predictors than subjective preferences are. On the other hand, however, these preferences might reflect individual differences with respect to the temperature allowing for optimal performance. If so, subjective preferences might be more reliable performance predictors than objective temperature is.

Although it is reasonable to assume a role of subjective preferences in modulating the relationship between temperature and cognitive performance, empirical studies investigating this possibility are lacking. Here, we tested the relationship between objective temperature and subjective temperature preferences in predicting performance in simple or complex cognitive tasks. Given the available evidence, performance should be worse under warmer temperatures, and this effect should be stronger for more complex tasks. Conversely, if subjective preferences modulate this effect, performance should be worse under the less preferred temperature, irrespective of the objective temperature, and this effect should be stronger for more complex tasks. We compared these two hypotheses by employing the N-back task (see Kane, Conway, Miura, & Colflesh, 2007, for a review), a task tapping the ability to monitor and update information in working memory (WM)—a key cognitive control function (Miyake et al., 2000).

In the N-back task, participants are presented with a sequence of stimuli and decide whether each stimulus matches the one appearing *n* items ago. The task gets more difficult as *n* increases, since this requires more online monitoring, updating, and manipulation of remembered information. We used two conditions: In the 1-back condition, each stimulus was to be compared with its direct predecessor, which minimizes reliance on WM resources. In the 2-back condition, each stimulus was to be compared with the one presented two trials before, which implies a higher memory load and greater demands on control resources. The typical finding is that participants' accuracy is lower in the more demanding condition (i.e., the 2-back) than in the less demanding one (i.e., the 1-back condition; see Kane et al., 2007), an observation that fits with the assumption that cognitively challenging tasks suffer more from the depletion of cognitive resources as compared to easier tasks (Baumeister et al., 1998; see also Colzato, Jongkees, Sellaro, & Hommel, 2013a).

Once recruited, participants underwent to a brief survey that allowed us to divide them into two groups on the basis of their favorite temperature: warm-preferred (WP) and cold-preferred (CP). In Experiment 1, participants were asked to perform the N-back task in a testing room whose temperature was ≈20 °C. This provided us with a baseline associated with performance in the 1-back and the 2-back conditions at a regular office temperature. In Experiment 2, we experimentally manipulated the room temperature to be cold (≈15 °C) versus warm (≈25 °C) within participants (in a counterbalanced order) to compare the effects of preferred and objective temperature on participants' performance.

Experiment 1

Method

Participants

Twenty-eight young healthy adults (2 men and 26 women) were compensated for their participation. They constituted the two groups of 14 warm-preferred (WP) and 14 cold-preferred (CP) participants. The sample was drawn from 41 adults, who volunteered to participate in behavioral studies. All participants were naïve regarding the purpose of the experiment.

Following Colzato, van den Wildenberg, Zmigrod, & Hommel (2013b) to avoid the possibility that expectations and motivation drive group differences in the cognitive task, participants were recruited through a covert recruitment strategy. Participants filled in a questionnaire that assessed their preferred temperature over other preferences and habits (i.e., religious belief and their familiarity with video games). Specifically, participants were asked the following questions: (1) Are you baptized? (2) How often do you pray? (3) How often are you going to the church? (4) Do you prefer the heater high or low? (5) Do you work/study better when the heater is high or low? (6) Do you play video games? (7) Which kind of video games do you play? (8) How often do you play? Participants' responses to the questions about temperature preference were used to classify them as WP, CP, or "neither" (i.e., participants who did not express any preference and/or whose responses to the temperature questions were not consistent with each other).

A week after the completion of the questionnaire, the participants classified as WP and CP, but not "neither" ($n = 13$), were invited to take part in the testing session, without revealing why they were being recruited. Demographic statistics are provided in Table 1.

Written informed consent was obtained from all participants; the protocol and the remuneration arrangements of 3 euro were approved by the local ethical committee (Leiden University, Institute for Psychological Research).

Table 1 Experiment 1: demographic characteristics, mean RTs (in ms), and mean proportions of correct responses (accuracy), hits, correct rejections, false alarms, and misses for the N-back task for warm-preferred (WP) and cold-preferred (CP) participants

Variables	Warm-preferred	Cold-preferred
N (F:M)	14 (13:1)	14 (13:1)
Age	22 (.85)	20 (.85)
N-back (WM monitoring/updating)		
1-back		
Reaction times	530 (15.6)	511 (15.6)
Accuracy	0.95 (.01)	0.94 (.01)
Hits	0.91 (.01)	0.94 (.01)
Correct rejections	0.97 (.01)	0.94 (.01)
False alarms	0.03 (.01)	0.06 (.01)
Misses	0.09 (.01)	0.06 (.01)
2-back		
Reaction times	596 (16.3)	559 (16.3)
Accuracy	0.87 (.02)	0.88 (.02)
Hits	0.85 (.03)	0.83 (.03)
Correct rejections	0.88 (.02)	0.91 (.02)
False alarms	0.12 (.02)	0.09 (.02)
Misses	0.15 (.03)	0.17 (.03)

Standard errors of the mean are shown within parentheses

Apparatus and procedure

The experiment was controlled by a PC running under Windows, attached to a Philips 109B6 17-inch monitor (LightFrame 3, 96 dpi with a refresh rate of 120 Hz). Responses were made by pressing the left shift key and the right shift key of the QWERTY computer keyboard with the left and right index finger, respectively.

All participants were tested individually, and each participant took part in a single testing session in which the room temperature was ≈ 20 °C.

Upon arrival, participants were asked to rate their mood on a 9×9 pleasure $\times$ arousal grid (Russell, Weis, & Mendelsohn, 1989) with values ranging from –4 to 4. Afterward, participants were asked to perform the N-back task, which provides a well-established diagnostic measure of WM monitoring and updating (Kane et al., 2007). Halfway through the N-back task, participants were asked to rate their mood for the second time. Finally, at the end of the N-back task, participants again rated their mood.

N-back task The two conditions of the N-back task were adopted from Colzato et al. (2013b). A stream of single visual letters (taken from B, C, D, G, P, T, F, N, and L) was presented (stimulus–onset asynchrony 2,000 ms; duration of presentation 1,000 ms). Participants responded to targets (presented in 33 % of the trials) and to nontargets.

Half of the participants pressed the left shift key in response to a target and the right shift key in response to a nontarget; the other half of the participants received the opposite mapping. Target definition differed with respect to the experimental condition. In the 1-back condition, targets were defined as stimuli within the sequence that were identical to the immediately preceding one. In the 2-back condition, targets were defined as stimuli within the sequence that matched the one that was presented two trials before. Each block consisted of four cycles of the same task; each cycle comprised of 32 stimuli.

Statistical analyses

The two scales (arousal and pleasure) of the Affect Grid were analyzed separately by means of repeated-measures analyses of variance (ANOVAs) with time (first vs. second vs. third measurement) as within-subjects factor and (temperature) preference (WP vs. CP) as between-subjects factor.

For the N-back task, repeated-measures ANOVAs with task load (1-back vs. 2-back) as within-subjects factor and preference (WP vs. CP) as between-subjects factor were carried out on correct reaction times (RTs) and on accuracy (i.e., proportions of correct responses to both target and nontarget stimuli), hits (i.e., proportions of correct responses to target stimuli), correct rejections (i.e., proportions of correct responses to nontarget stimuli), false alarms (i.e., incorrect responses to nontarget stimuli), and misses (i.e., proportions of target stimuli not responded to) after arcsine transformation of proportions. Table 1 shows mean RTs (in ms) and the means of the untransformed data (i.e., mean proportions) for accuracy, hits, correct rejections, false alarms, and misses for the N-back task for WP and CP participants.

A significance level of $p < .05$ was adopted for all statistical tests.

Results

N-back

Load was significant for all dependent variables. Higher load increased RTs, $F(1,26) = 19.03$, $p = .0001$, MSE = 2,423.216, $\eta_p^2 = 0.42$ and, more importantly, it reduced accuracy, $F(1,26) = 45.99$, $p = .0001$, MSE = 0.005, $\eta_p^2 = 0.64$. Furthermore, compared to lower load, higher load produced fewer hits, $F(1,26) = 22.33$, $p = .0001$, MSE = 0.011, $\eta_p^2 = 0.46$, and correct rejections, $F(1,26) = 24.18$, $p = .0001$, MSE = 0.009, $\eta_p^2 = 0.48$, but more false alarms, $F(1,26) = 24.18$, $p = .0001$, MSE = 0.009, $\eta_p^2 = 0.48$, and misses, $F(1,26) = 22.33$, $p = .0001$, MSE = 0.011, $\eta_p^2 = 0.46$. Importantly, for all dependent

Table 2 Experiment 2: demographic characteristics, mean RTs (in ms), and mean proportions of correct responses (accuracy), hits, correct rejections, false alarms, and misses for the N-back task for warm-preferred (WP) and cold-preferred (CP) participants in the warm and cold sessions

Variables	Warm-preferred		Cold-preferred	
N (F:M)	13 (6:7)		14 (10:4)	
Age	25.5 (0.8)		23.4 (1.0)	
N-back (WM monitoring/updating)	Warm temperature	Cold temperature	Warm temperature	Cold temperature
1-back				
Reaction times***	436 (15.9)	513 (17.8)	492 (15.3)	424 (17.2)
Accuracy	0.96 (.01)	0.94 (.01)	0.94 (.01)	0.96 (.01)
Hits	0.94 (.01)	0.94 (.01)	0.92 (.01)	0.95 (.01)
Correct rejections	0.98 (.01)	0.94 (.01)	0.95 (.01)	0.97 (.01)
False alarms	0.02 (.01)	0.06 (.01)	0.05 (.01)	0.03 (.01)
Misses	0.06 (.01)	0.06 (.01)	0.08 (.01)	0.05 (.01)
2-back				
Reaction times***	474 (19.5)	577 (22.3)	601 (18.8)	507 (21.5)
Accuracy**	0.93 (.02)	0.86 (.02)	0.85 (.02)	0.92 (.02)
Hits**	0.89 (.03)	0.78 (.02)	0.84 (.03)	0.91 (.02)
Correct rejections	0.96 (.02)	0.91 (.02)	0.87 (.02)	0.93 (.02)
False alarms	0.04 (.02)	0.09 (.02)	0.13 (.02)	0.07 (.02)
Misses**	0.11 (.03)	0.22 (.02)	0.16 (.03)	0.09 (.02)

Standard errors of the mean are shown within parentheses

Significant difference between the two temperatures; *** $p < 0.005$, ** $p < 0.01$

variables, neither the main effect of preference nor the interactions between load and preference were significant, $F_s \leq 3.26$, $p_s \geq .08$.

Mood

ANOVAs performed on pleasure (0.8 vs. 0.2 vs. 0.6 and 1.5 vs. 1.5 vs. 1.3 for WP and CP participants, respectively) and arousal (0.5 vs. 0.3 vs. 1.0 and 0.7 vs. 1.2 vs. 1.1 for WP and CP participants, respectively) scales revealed no significant main effects nor any interactions, $F_s \leq 4.03$, $p_s \geq .06$.

Discussion

The results of Experiment 1 show that for both WP and CP participants, performing the N-back task at a regular office temperature of $\approx$20 °C was associated with the typical performance observed in previous studies (Kane et al., 2007; Colzato et al., 2013a, b), in which participants' accuracy—the most sensitive dependent variable of this task (Kane et al., 2007)—is significantly reduced in the more demanding task. Most importantly, these results represent a suitable baseline to assess the possible role of the objective temperature and the subjective (temperature) preferences in modulating participants' performance and to determine the specific impact of either factor.

Experiment 2

Method

Participants

A new sample of twenty-eight participants (11 men and 17 women) was selected from a pool of 40 young healthy adults by means of the same covert recruitment strategy employed in Experiment 1. Based on their answers about the temperature questions, the participants classified as WP ($n = 14$) and CP ($n = 14$), but not "neither" ($n = 12$) took part in the testing session. One participant (WP) was excluded because of technical problems in the laboratory. Demographic statistics are shown in Table 2.

All participants were naïve about the purpose of the experiment, and they did not take part in Experiment 1.

Written informed consent was obtained from all participants; the protocol and the remuneration arrangements of 6.5 euro were approved by the local ethical committee (Leiden University, Institute for Psychological Research).

Apparatus and procedure

The apparatus and procedure were the same as those in Experiment 1 with the following exceptions. Participants took part in two experimental sessions (manipulating temperature), separated by 3–7 days. In each session, the room temperature was experimentally manipulated to be cold (≈15 °C) versus warm (≈25 °C). The order of the two temperature conditions was counterbalanced across participants. As in Experiment 1, in each session, mood data (pleasure × arousal grid; i.e., Russell et al., 1989) were collected in three different moments: upon participants' arrival, after having completed the 1-back task, and at the end of the 2-back task.

Statistical analyses

The Arousal and Pleasure scales were submitted to separate ANOVAs with temperature (warm vs. cold) and time (first vs. second vs. third measurement) as within-subjects factors and preference (WP vs. CP) as between-subjects factor.

For the N-back task, ANOVAs with task load (1-back vs. 2-back) and temperature (warm vs. cold) as within-subjects factors and preference (WP vs. CP) as between-subjects factor were performed on correct RTs, accuracy, hits, correct rejections, false alarms, and misses. As in Experiment 1, all proportions were subjected to arcsine transformations before analyses. Table 2 shows mean RTs (in ms) and the mean proportions of accuracy, hits, correct rejections, false alarms, and misses for the N-back task for WP and CP participants in the warm and cold sessions.

Newman–Keuls post hoc analyses were performed to clarify mean differences in case of significant interactions. A significance level of $p < .05$ was adopted for all statistical tests.

Results

N-back

Load affected all dependent measures, showing that higher load increased RTs, $F(1,25) = 30.96$, $p = .0001$, MSE = 4,203.079, $\eta_p^2 = 0.55$, and reduced accuracy, $F(1,25) = 21.43$, $p = .0001$, MSE = 0.012, $\eta_p^2 = 0.46$. Higher load also produced fewer hits, $F(1,25) = 21.94$, $p = .0001$, MSE = 0.018, $\eta_p^2 = 0.47$, and correct rejections, $F(1,25) = 15.15$, $p = .001$, MSE = 0.011, $\eta_p^2 = 0.38$, but more false alarms, $F(1,25) = 15.03$, $p = .001$, MSE = 0.011, $\eta_p^2 = 0.38$, and misses, $F(1,25) = 22.04$, $p = .0001$, MSE = 0.017, $\eta_p^2 = 0.47$, than the lower load did. Of particular interest, the main effects of temperature and preference were not significant ($F_s \leq 1.39$, $p_s \geq .25$).

The interaction between preference and temperature was significant for all dependent measures: accuracy, $F(1,25) = 45.55$, $p = .0001$, MSE = 0.004, $\eta_p^2 = 0.65$, RTs, $F(1,25) = 105.32$, $p = .0001$, MSE = 1,470.694, $\eta_p^2 = 0.81$, correct rejections, $F(1,25) = 51.15$, $p = .0001$, MSE = 0.004, $\eta_p^2 = 0.67$, false alarms, $F(1,25) = 52.63$, $p = .0001$, MSE = 0.004, $\eta_p^2 = 0.68$, hits, $F(1,25) = 15.51$, $p = .001$, MSE = 0.012, $\eta_p^2 = 0.38$, and misses, $F(1,25) = 15.80$, $p = .001$, MSE = 0.011, $\eta_p^2 = 0.39$, thus revealing that participants' performance was modulated by their temperature preference. Specifically, post hoc analyses showed that, for all aforementioned variables, WP participants exhibited better performance in the warm than in the cold session ($p_s \leq .03$), whereas the opposite pattern was observed for CP participants, i.e., they showed better performance in the cold than in the warm session ($p_s \leq .03$).

Most importantly, significant interactions between load, temperature, and preference were observed for RTs, $F(1,25) = 13.887$, $p = .001$, MSE = 429.331, $\eta_p^2 = 0.36$, hit, $F(1,25) = 8.27$, $p = .008$, MSE = 0.008, $\eta_p^2 = 0.25$, misses, $F(1,25) = 9.03$, $p = .006$, MSE = 0.007, $\eta_p^2 = 0.27$, and, crucially, for accuracy, $F(1,25) = 8.60$, $p = .007$, MSE = 0.004, $\eta_p^2 = 0.26$, but not for false alarms and correct rejections ($F_s \leq 2.66$, $p_s \geq .12$). Post hoc analyses revealed that, in the 1-back task, for both WP and CP participants performance in terms of hits, misses and accuracy was comparable when tested under the preferred and non-preferred temperature ($p_s \geq .12$). In contrast, in the 2-back task, participants' accuracy improved significantly when tested under the preferred temperature: WP participants showed fewer misses, higher hits and were more accurate in the warm than in the cold session ($p_s \leq .0005$), whereas CP participants showed fewer misses, higher hits and were more accurate in the cold than in the warm session ($p_s \leq .02$; see Table 1 and Fig. 1). With regard to RTs, WP were faster in the warm than in the cold session, whereas CP participants were faster in the cold than in the warm session, in both the 1-back and the 2-back tasks ($p_s \leq .0001$). The interactions between load and temperature and between load and session were not significant, $F_s \leq 2.19$, $p_s \geq .15$.

Mood

The ANOVA performed on the Arousal scale did not reveal any significant effect or interaction, $F_s \leq 1.46$, $p_s \geq .24$, thus indicating that neither the subjective preference nor the objective temperature affected the arousal levels (arousal was −0.1 vs. −0.1 vs. 0.2 and 0.2 vs. −0.6 vs. −0.2 in the warm and cold sessions, respectively, for

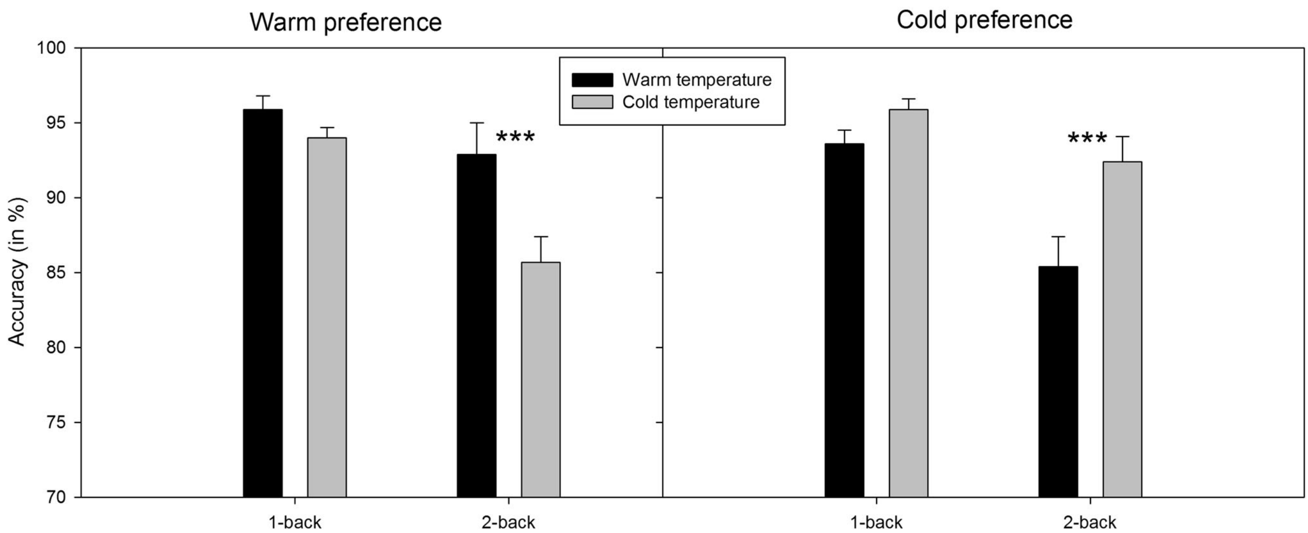

Fig. 1 Experiment 2: mean accuracy (in %) as a function of load (1-back vs. 2-back), temperature (warm vs. cold), and preference (WP vs. CP). *Asterisk* indicates significant differences (***$p < .001$) between the two experimental sessions within each group of participants. *Vertical capped lines* atop *bars* indicate standard error of the mean

WP participants, and 0.1 vs. −0.2 vs. −0.3 and 0.1 vs. −0.1 vs. −0.3 in the warm and cold sessions, respectively, for CP participants). This suggests that we can rule out an account of our results in terms of arousal changes.

The ANOVA performed on the Pleasure scale revealed a significant three-way interaction between temperature, time, and preference, $F(1,24) = 4.12$, $p = .03$, $\mathrm{MSE} = 2.63$, $\eta_p^2 = 0.26$. Post hoc analyses showed that for WP participants, pleasure was not affected by the room temperature (0.4 vs. 0.5 vs. 1.0 and 0.8 vs. 1.1 vs. 0.7 in the warm and cold session, respectively, $p_s \geq .73$). In contrast, for CP participants, analyses revealed that although in both the cold (1.3 vs. 1.0 vs. 1.9) and the warm (1.4 vs. 1.3 vs. 0.4) sessions, pleasure levels were constant across the three measurements, $p_s \geq .32$, at the third measurement, these participants experienced more pleasure in the cold than in the warm session, $p = .047$. Note that the fact that these participants experienced more pleasure when working under the preferred temperature condition but only at the third measurement cannot account for the results observed in the N-back task. All the other main effects and interactions were not significant, $F_s \leq 1.65$, $p_s \geq .21$.

Discussion

The results of this experiment suggest that the preferred but not the objective temperature modulates participants' performance in the N-back task. Specifically, we observed that working under the preferred temperature condition can promote WM updating. As expected, the more challenging 2-back condition was more sensitive to the beneficial effect of the preferred temperature—an observation that fits with the concept of ego-depletion (Baumeister et al., 1998) and with the assumption that only cognitively demanding (and, thus, resource-consuming) tasks benefit from factors that can promote cognitive enhancement, as suggested by a more recent finding (Colzato et al., 2013a).

To strengthen this conclusion, we performed additional contrasts to compare performance of participants in Experiments 1 and 2. Results showed that, compared to the participants of Experiment 1 who performed the task at a regular office temperature of ≈20 °C, those of Experiment 2 showed higher accuracy in the 2-back condition when performing the task under the preferred temperature condition ($F_s \geq 4.38$, $p_s \leq .046$). Importantly, performance in the 2-back condition under the non-preferred temperature condition was comparable to the performance shown by participants of Experiment 1 ($F_s \leq 1.34$, $p_s \geq .55$), which can be assumed to be reflect the typical performance observed in the N-back task in standard conditions. For the 1-back task, performance of participants of Experiment 1 was completely comparable with the performance shown by participants of Experiment 2 in both the warm and the cold sessions ($F_s \leq 2.72$, $p_s \geq .11$).

General discussion

This study is the first to suggest that individual temperature preferences might be a better predictor of cognitive performance than objective temperature measures. In keeping with the literature, neither objective nor subjective temperature measures predicted performance in the simple task. This supports previous assumptions that temperature only affects resource-demanding cognitive operations (Hancock & Vasmatzidis, 2003). Crucially, we obtained neither a main effect of room temperature nor an interaction between temperature and load. Since some of the previous studies showing heat-related deficits used higher temperature (Hancock et al., 2007; Pilcher, Nadler, & Busch, 2002), our findings are not in contrast with such observations: Using more extreme temperatures than those we considered might cause a temperature main effect. Yet, within the temperature range that we considered (which produced main effects in some studies; e.g., Cheema & Patrick, 2012), subjective preferences were more reliable performance predictors than objective temperatures. Hence, although our findings may not speak to situations of extreme heat stress, we can conclude that subjective preferences, together with the environmental conditions satisfying them, play an important role in regulating ego-depletion in challenging tasks. It would be interesting to see whether these observations can be extended to other cognitive control functions.

Taken together, our findings can have important practical implications for the design of workspaces by underlining how important is to take into consideration individual differences and subjective preferences. Indeed, these results suggest that working under the preferred temperature condition may lead to an increment of efficiency and productivity. Note, however, that the exposure time to both the preferred and the non-preferred temperatures was relatively short. Thus, it is necessary for further studies to verify whether the performance improvements observed in the current study remain with longer exposure times and/or whether longer exposure times to non-preferred temperature may cause performance deteriorations.

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