Hot under the Collar: The Impact of Heat on Game Play

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Abstract

High temperatures have been documented to affect behavior in a variety of ways depending on the nature of the task. We extended this prior research by examining the effects of dynamically changing temperature on various aspects of performance in a video game task. In the span of approximately an hour, temperature was gradually increased, stayed constant for a period of time, and gradually decreased to baseline. The gaming task was a variation on one used to assess impulsivity in participants thus allowing the possibility of assessing the effects of temperature on impulsive choice. Rather than heat increasing impulsivity and thus decreasing wait times, participants showed increases in wait times as temperature increased which either suggests that participants were becoming more self-controlled under heat or that the documented negative impact of heat on motor functioning was dominating their performance. Importantly, the participant's sensitivity to the changing task requirements was not affected by changes in temperature.

1. Introduction

Human performance is demanded under a range of environmental conditions, even in the climate-controlled offices of today. More extreme conditions are usually reserved for those who work outside, on many factory floors, or while wearing protective gear with poor ventilation. But, even office workers occasionally can be seen wearing sweaters and gloves, using personal fans, or working with the windows open because the ventilation system is not working properly. Not surprisingly, scientists have conducted research on the effects of temperature extremes on various aspects of human performance. The goal of the current project was to examine the impact of the dynamics of warming and subsequent cooling on performance in a complex task.

There is a long history of the study of the effects of extreme temperature environments on behavior and physiology. The extent of this research is in part due to the number of disciplines that have examined the effects of extreme environments on humans that include, but are not limited to, psychology Helton (2010); (Wearden & Penton-Voak, 1995), physiology (Wright, Hull, & Czeisler, 2002), engineering (Elson & Eckels, 2015; Fang, Wyon, Clausen, & Fanger, 2004) and neuroscience (Hocking, Silberstein, Lau, Stough, & Roberts, 2001; Paulus et al., 2009).

Thermal environment performance research has tended to focus on three general areas of performance: psychomotor, perceptual, and cognitive. The meta-analysis by Hancock, Ross, and Szalma (2007) examined 49 articles encompassing 57 studies that assessed one or more of these performance measures in at least one extreme temperature environment. They derived 181 effect size estimates for cold environments and 347 for hot environments. Overall, it was found that performance was 11% worse under thermal stressors as compared to control conditions, representing about a third of a standard deviation drop in performance (Hedges g = -0.34 with a

95% Confidence Interval of [-0.41, -0.27]). A closer examination of the results indicated that there were differences in effect size based on temperature, task, and duration of exposure.

For example, using both psychomotor and cognitive tasks of sustained attention and serial responding, Razmjou and Kjellberg (1992) exposed participants to control (22˚ C) and heat (40˚ C) conditions one week apart while measuring reaction time for two tasks. The first task required participants to press the space bar of a computer every time a red light illuminated; this task was judged to be a task dominated by psychomotor components. The second task had participants indicate which arm of a cross was longer, a task judged to require more cognitive effort. While completing these tasks, participant core body temperature and heart rate were monitored. Results demonstrated very little difference in performance for the two tasks in the control condition. However, the heat condition produced significantly more errors on the cognitive cross arm length task, whereas heat produced longer reaction times on the psychomotor red light response task; thus, the performance deficit caused by increased temperature was different on the two tasks. This type of result is typical – even in simple tasks with two performance measures, temperature can impact performance on one measure but not another; furthermore, which measure is affected can differ across tasks. The interpretation, however, is complicated by the fact that even simple tasks require at least some degree of psychomotor, perceptual, and cognitive processing which makes it difficult to isolate the particular effect of a manipulated variable like temperature and how this research will translate to more complex tasks.

Our project examined the effect of heat on performance in a complex video game task, so we focused our attention on prior research examining the effects of heat on particular task components. Gaoua, Racinais, Grantham, and Massioui (2011) had participants complete five different cognitive tasks (three attention and two memory) in three different thermal conditions (20˚ C, 50˚ C, and 50˚ C with head cooling). They sought to examine particular cognitive deficits caused by increased temperatures and documented significant effects on inhibition with rapid visual processing tasks (with more false alarms occurring during the heat condition without head cooling) and significant negative effects on both their spatial span memory and pattern recognition tasks. In Hancock et al.'s meta review, the average effect of heat on performance varied as a function of the type of measure with the largest effects occurring for tasks judged to be psychomotor (decreasing accuracy, $g = -.59$, and increasing reaction times, $g = .68$) or perceptual (paradoxically by decreasing reaction times, $g = -.91$, while decreasing accuracy, $g = -.41$, suggesting a speed-accuracy tradeoff).

1.1 Heat and Impulsivity

The present study involved a task designed to study people's ability to exhibit self-control when the task conditions necessitate doing so to optimize performance. Using temperature as a metaphor to describe people's propensity toward self-control is common. Some people are hotheaded while others are cold and rational. Decisions made in the "heat of the moment" or in the "heat of the battle" are considered impulsive because they are made quickly. In an attempt to determine if this analogy could drive behavioral change in the expected direction (heat producing more impulsive choice), Ahn (2010) performed two field studies in which participants in two temperature conditions (a hot spa, 40-50˚C, and a cold spa, 10˚C; the second study added a very hot spa, 80˚C, condition) completed a questionnaire that included willingness to pay questions and a standard delay discounting questionnaire (Rachlin, Raineri, & Cross, 1991) as indices of impulsivity. In general, they found results consistent with their predicted association between heat and a greater willingness to pay or preference for a smaller sooner reward over a larger later award. Although intriguing, these same effects were observed when the participant was merely primed by words or pictures associated with heat and cold (e.g., a summer versus a winter scene). The verbal nature of the assessment and the known associations between heat and impulsivity may have created some demand characteristics that limit the generalization of the study conclusions to more implicit assessments of impulsivity.

There are numerous reasons why exposure to heat could affect choice beyond a merely metaphorical association. Exposure to hot temperatures increases heart and respiration rates, deepens respiration, increases blood circulation, skin blood vessel dilation, sweating and the galvanic skin response, and decreases basal metabolic rate (Anderson, 1989). This multidimensional impact of heat on physiology could impact behavior. For example, Helton (2010) had participants complete a sustained attention response task while measuring tympanic membrane (ear canal) temperature. Measuring tympanic membrane temperature is thought to indicate hemisphere specific blood flow (Helton, Hayrynen, & Schaeffer, 2009). As predicted, it was found that as right tympanic membrane temperatures increased (this hemisphere has been shown to be important to inhibition, Aron, Robbins, & Poldrack, 2004, 2014; Garavan, Ross, & Stein, 1999); there were fewer errors of commission (r = -0.78) and reaction time increased (r = .34), consistent with greater inhibition.

The current study introduces a change to previous methodologies to further our understanding of heat on cognitive processes. All prior behavioral studies had participants perform a task in one of two or more constant temperature environments (e.g., control vs. hot). In our study, we chose to examine the within-subject effects of temperature by dynamically changing room temperature while participants performed an ongoing task requiring varying degrees of self-control. A natural design to examine the effects of temperature change on performance would have been to assess performance as the temperature gradually increased or decreased in the environment. However, interpretation of any changes in performance as a function of temperature would have been confounded with other variables affecting performance over time – learning, fatigue, and boredom. In previous work using a similar self-control task (Young, Webb, & Jacobs, 2011; Young, Webb, Rung, & McCoy, 2014), participants tended to wait longer and show greater reward sensitivity as the game proceeded (without temperature variation). Thus, we were faced with two alternatives, either include a control condition in which temperature was not varied or decorrelate temperature from these other factors affecting performance. We chose to decorrelate temperature with the effects of learning, fatigue, and boredom which change monotonically across time by having temperature change non-monotonically across time: a gradual increase in temperature was followed by a stable hot period and then a gradual decrease to the baseline temperature. Thus, the monotonic effects over time of these other variables would be uncorrelated with the non-monotonic change in temperature over time. This design also allowed us to measure and analyze thermal comfort in dynamic temperature environments; this more physiological analysis is reported in a separate manuscript (Eckels, Schlabach, Young, & Eckels, 2016).

Manipulating temperature dynamically allows for a number of possible effects of heat on task performance. Because the task assesses self-control by the amount of time that participants wait between responses (shorter wait times = greater impulsivity), it is possible that hotter conditions would create less waiting due to a decrease in self-control created by the heat. But, it is also possible that the tendency for heat to increase reaction times in psychomotor and cognitive tasks (Hancock et al., 2007) might produce longer waiting between responses. Our task also includes a second measure of performance; the outcome advantages of waiting changes throughout the task allowing us to assess participant sensitivity to these changes and thus their task attention and engagement. In previous research, we have commonly observed increased sensitivity as the task proceeds (Webb & Young, 2015; Young, Webb, Sutherland, & Jacobs, 2013). If heat negatively impacts general cognitive performance, then we would expect a negative relationship between sensitivity to the changing waiting contingency and room temperature.

1.2 The Task and Our Hypotheses

The behavioral assessment entails participants playing a custom-designed video game. They were tasked with destroying their targets in the game, and longer waiting between each shot allows the weapon to recharge and thus do more damage with each shot. However, the way that the weapon recharges dictates whether waiting produces a higher damage rate or a lower damage rate (Young et al., 2011). The recharge function changes at regular intervals, and the participant needed to adapt to these changes in order to destroy the targets more rapidly. We had two competing hypotheses regarding the effect of heat on how long participants would wait between shots:

> H1a: Higher temperatures will produce an increase in wait times due to psychomotor deficits caused by the heat.
>
> H1b: Higher temperatures will produce a decrease in wait times due to an increase in impulsivity caused by the heat.

We also had two competing hypotheses regarding the effect of heat on sensitivity to the changing reward contingencies:

> H2a: Higher temperatures will produce a decrease in sensitivity to the changes in wait-time contingencies due to attention deficits.
>
> H2b: Higher temperatures will produce an increase in sensitivity to the changes in wait-time contingencies due to a motivation to finish sooner and escape the uncomfortable temperatures.

It is also possible that neither effect would occur or that both of these competing hypotheses will be in operation and that their effects will cancel.

2. Method

2.1 Participants

The sample was exclusively male because female participants have more uncontrolled variation in their core temperature due to changes across the menstrual cycle which simplified the physiology modeling of subjects. A total of 30 healthy males ranging in age from 19 to 34 participated in the experiment. Subjects weighed between 65-100 kg and had a height between 1.70-1.95 m. Subjects were prescreened to ensure they were free of chronic disease with no history of heat-related illness, respiratory illness, skin disorder, or known allergy to adhesive tape. Subjects were required to refrain from the use of caffeine, nicotine, and alcohol for at least 24 hours prior to the experiment.

2.2 Procedure

Participants were prescreened by a medical professional to ensure their suitability for the temperature stresses used in the study. When a participant arrived at the Institute for Environmental Research, he entered the preconditioning chamber (3.4 × 3.4 × 2.7 m) where he was fitted with a standard set of clothing, weighed, and completed a basic demographic questionnaire that solicited data relevant for physiological modeling. The experimenters fit the participant with seven thermocouples to assess skin temperature and a chest strap heart rate monitor. Each participant spent 45 minutes in the preconditioning chamber which was maintained at a constant 25°C. At the end of preconditioning, the participant was moved to the primary chamber where they would be playing the video game.

The Torque Game Engine (obtained from www.garagegames.com) was adopted as the platform for game development. The game world included five levels each containing seven separate regions with each region populated by two visually-identical orcs (fictional monsters). The landscape and orcs were identical across game levels. For simplicity, the orcs were stationary, and each orc in a region was oriented toward a target region (e.g., a building) that the player was directed to protect. Every 4 s (on average), each orc fired its weapon. The player's task was to destroy all of the orcs within each game level.

After a player fired the weapon, it recharged over a 10 s period. The way in which it recharged was determined by the following equation:

$$damage = 100 \cdot \left(1 - \left(\frac{(10 - t)}{10}\right)^{power}\right)^{1/power} \qquad (1)$$

The value of the *power* parameter determined whether firing more rapidly would destroy the orc more quickly (when *power* > 1.0) or if waiting the full 10 s was optimal (when *power* < 1.0); for power values farther from 1.0, the penalty for a suboptimal choice was greater – it would take an increasingly longer time to destroy an orc. The power value of the weapon changed each time the participant destroyed two orcs. We used a Halton sequence (Halton, 1964) stimulus sampling design in which the power value was chosen from the 0.5 to 1.5 range; thus, each participant received the same values in the same order. The change in a weapon's power was accompanied with a three-tone sequence with a pitch that was correlated with the new power level.

In our analyses, we dropped interresponse times (IRTs, equivalent to waiting time between shots) that exceeded 20 s in duration with the assumption that these were contaminated by inattention or excessive travel time. This resulted in a loss of 1.6% of the data with no more than 4.5% lost from any single participant. Because the IRTs were strongly bimodal which was consistent with the task contingencies determined by the power value of Equation 1, IRTs were dichotomized such that those less than 5 s were classified as ‘not waiting’ whereas those greater than 5 s were classified as ‘waiting’.

2.2.1 Temperature Manipulation. The primary environmental chamber (5.5 × 7.0 × 3.8 m) used low flow (< 0.25 m/s) to regulate temperature (this rate is close to still air and reduces possible draft discomfort complications); this chamber contained a laptop, a desk, and a chair where the participant was seated. The environmental conditions in this chamber were set by two primary variables: the dry bulb temperature and the wet bulb temperature. This manipulation served to control both temperature and humidity (55% relative humidity). The temperature in the primary chamber was set to follow a transient profile during the measurement phase of the experiments as shown in Figure 1. The first 25 minutes of the test increased the temperature from 25°C to 40°C at a constant rate. Temperature then remained constant until the subject finished the third level of the video game at which time the temperature decreased to baseline at the same rate and remained at 25°C for the remainder of game play. The exact final temperature of the chamber depended on the amount of time required for the subject to complete the final two levels. The relative humidity for the chamber was set at a constant 55%.

2.2.2 Physiological Testing and Other Assessments. A range of other assessments were performed for use in a parallel study (Eckels et al., 2016). We will only provide a brief summary; for details, see Eckels, et al. In addition to the constant monitoring of skin temperature and heart rate, the experimenters conducted a metabolic cart analysis before the beginning of game play and at the end of the study (this analysis assesses a range of physiological measures of metabolism). Between game levels and at the end of the game, whole body thermal comfort and sensation were measured using the Berkley comfort scale (Arens, Zhang, & Huizenga, 2006) and the ASHRAE 7-point sensation scale (ASHRAE, 1966). The experimenters also assessed tympanic membrane temperature before and after the experiment and between game levels.

3. Results

Although a wide range of data were collected for other purposes, for this manuscript we focused our attention on the video game performance data and how it related to the air temperature in the chamber. Because the video game data were continuously collected during the experiment, we used a temperature measure that was likewise continuously collected throughout the game. During play, we had two physical measures of temperature: air temperature and skin temperature. Because skin temperature was collected at seven different locations and varied over a narrower temperature range (31.1˚C to 36.8˚C versus 24.8˚C to 43.3˚C for air temperature), we chose to use air temperature because of its greater range and statistical reliability. We do note that air and skin temperature were very highly correlated (r = .90, SE = .01) for individual participants (i.e., we computed correlations for each subject), and average air temperature during a level and the tympanic membrane temperature collected immediately following that level were highly correlated for each participant (r = .76, SE = .03). Tympanic membrane temperatures moved from an average of 36.7˚C before game onset to 37.5˚C after the third level (when most participants experienced the highest air temperature) and dropped to 36.6˚C after game completion. Individual participants showed a range (maximum minus minimum) of tympanic membrane temperature between 0.3˚ to 2.1˚C with an average individual range of 1.2˚C.

Figure 1 shows the changes in air temperature as a function of time within each game level for each participant. Because participants took different amounts of time to complete the game level, there was some variation in the relationship between game level and experienced temperature. However, four participants experienced different temperature dynamics due to experimenter error. One participant experienced a higher maximum temperature (43.3˚C), one participant experienced a delayed temperature rise, and two participants did not experience the programmed decrease before game play ended. We dropped these four participants from the analysis; their exclusion caused the magnitude of a single two-way interaction involving air temperature and power (the variable that determines the advantages of waiting) to decrease by 56% and become non-significant.

Because the outcome variable (interresponse time or IRT) was highly bimodal, we dichotomized the IRTs as either being longer or shorter than 5 s; this approach is consistent with that used in earlier publications involving this video game task (e.g., Young, Webb, Rung, & Jacobs, 2013; Young et al., 2014). We fit the data using a multilevel logistic regression with air temperature, game time, and power (from Equation 1) as main effects and two-way interactions between power and the other variables (as moderators) to identify any effects of temperature on sensitivity to the power changes while controlling for effects of game time on power sensitivity. All predictors were mean-centered, and game time elapsed was divided by 2000 to rescale it to values in the same range as the other predictors; this rescaling was done to ensure model convergence.

The resulting parameter estimates are shown in Table 1, and a plot of the effects of air temperature and power on the likelihood of waiting are shown in Figure 2 (game time elapsed was set to its average, 2022 s, for this plot). Participants clearly showed the expected sensitivity to the changing contingencies for waiting (i.e., power). There was a significant effect of temperature on waiting, with participants waiting longer between shots when the chamber was hotter which is consistent with hypothesis H1a. Although waiting also tended to increase monotonically as the game proceeded (see Table 1), the effect of the non-monotonic variation in temperature was clearly evident. The mean IRT as a function of game time is shown in the right panel of Figure 3 with air temperature dynamics plotted in the left panel. Although this IRT plot does not control for learning or fatigue, the increase in IRTs during the hottest period in the middle of the game was followed by shorter IRTs during the cooling down period, consistent with the temperature dynamics.

Notably, there was a lack of evidence for an interaction between temperature and power indicating that sensitivity to the waiting contingency was not affected by the temperature. There also was a lack of evidence of a change in sensitivity as the game proceeded (i.e., no power × time interaction).

4. Discussion

While playing a video game under changing temperature conditions, participants increased their wait time between shots consistent with Hypothesis H1a. This result suggests that the predominant effect of heat on task performance was to create a psychomotor deficit rather than an increase in impulsivity. Participants also showed a small increase in wait times as the task progressed, consistent with other reports involving this task (e.g., Young et al., 2011; Young et al., 2014). Sensitivity to the changing contingencies (assessed by the slope of the *power* predictor, Table 1), however, did not change as a function of temperature suggesting that either heat had no effect or that Hypotheses H2a and H2b offset one another. One interesting aside is that there was no observed increase in sensitivity as the task proceeded. However, earlier reports involving this task have generally reported power slopes between -1.0 and -2.0 (Webb & Young, 2015; Young et al., 2011) whereas the present experiment documented a slope near -3.0. Given that our participants were paid and that they were specifically recruited to participate in a video game study, the overall high level of sensitivity and the absence of learning effects may reflect these task and participant differences increasing motivation.

Previous experiments on heat and performance have attempted to assess behavior using very simple tasks that often lack external validity. The advantage of such an approach is that it attempts to delineate specific task deficits or performance improvements created by increases in temperature. The disadvantage is that it can be difficult to generalize these results to a complex task that involves all of these task characteristics – perceptual, psychomotor, and cognitive. Our use of a complex gaming task allowed us to assess the heat responsiveness of specific task components including wait time and sensitivity to changing contingencies that are embedded within the task. Furthermore, we are the first to examine temperature dynamics on task performance rather than comparing conditions with different constant temperature levels.

We recognize that a single experiment cannot address all of the questions regarding the behavioral effects of heat. For practical reasons, it was necessary to use one non-monotonic manipulation of temperature (Figure 1). From a purely empirical aspect, questions remain regarding the effects of prolonged exposure to heat, the effect of different temperature dynamics (e.g., only increasing, only decreasing, the length of time the temperature was constant), individual differences in heat sensitivity, and additional performance metrics (e.g., efficient game navigation).

To truly understand the mechanics behind the observed effects, a richer assessment of the physiological impacts of heat on brain activity must be pursued to examine the specific relationships between brain activity and task performance under extreme heat conditions (Dalsgaard, Nybo, Cai, & Secher, 2003; Helton, 2010; Liu et al., 2013; Nielsen, Hyldig, Bidstrup, González-Alonso, & Christoffersen, 2001; Nielsen & Nybo, 2003; Paulus et al., 2009;

Rasmussen, Stie, Nybo, & Nielsen, 2004). However, a significant challenge arises in the pursuit of this goal – the problem with performing neural assessments in extreme temperature environments. For example, MRI equipment is almost exclusively located in temperature-controlled hospital environments, and this equipment is not designed to operate in extreme heat or cold (but see Jiang et al., 2013; Liu et al., 2013).

Although EEG is much more portable, the fact that heat increases scalp perspiration can create "bridging" between EEG electrodes – water is an electrical conductor, and high saline liquids like sweat will facilitate the transmission of electrical activity across adjacent electrodes making it difficult to identify the source of the electrical activity. This problem has been offset by the use of simple EEG preparations involving very few electrodes (often one or two) and a focus on EEG spectra rather than event-related potentials (ERPs) or source localization. For example, Rasmussen et al. (2004) used a single frontally-placed electrode to evaluate alpha and beta frequency bands at the site and reported an increased alpha/beta ratio when temperature increased; this increase indicates lower levels of alertness with increases in temperature during exercise (similar results were reported by Nielsen et al., 2001; Nielsen & Nybo, 2003, but all of these results increased temperature while exercising). The issue of bridging caused by perspiration in EEG, however, will create more of a challenge for an event-related analysis which may explain the dearth of ERP studies involving heat (we identified only one such study, Shibasaki, Namba, Oshiro, Crandall, & Nakata, 2016).

Interest in the effects of temperature on performance has surprisingly produced a long history but a long list of unanswered questions. Although there is a steady stream of published studies, the high degree of variability in designs and tasks, the performance of many of these studies in sub-optimal control environments, and the variation in effects of temperature on various aspects of behavior make it difficult to reach firm conclusions despite the decades of research. In some ways, the present study contributes to the variation in tasks and measures, but the complexity of the paradigm means that a single task can be used to assess multiple performance metrics. It will require a systematic series of studies to fully inform the mechanisms at play in complex tasks, and we plan to pursue such an approach. We encourage others to join us in this journey to shed more light than heat on these important questions.

Table 1. *Beta weights from a logistic regression of the likelihood of waiting as a function of power (see Equation 1), air temperature, and time in the game.*

	Estimate	SE	z	Pr(>|z|)
(Intercept)	0.115	0.251	0.459	0.646
Power	-2.987	0.488	-6.124	< .001
Air Temp	0.050	0.014	3.516	< .001
Time	0.308	0.155	1.987	0.047
Power*Air	-0.015	0.017	-0.852	0.394
Power*Time	-0.087	0.154	-0.566	0.571

Note: Power, Air Temp, and Time were all mean-centered for the regression. See Section 3 for details.

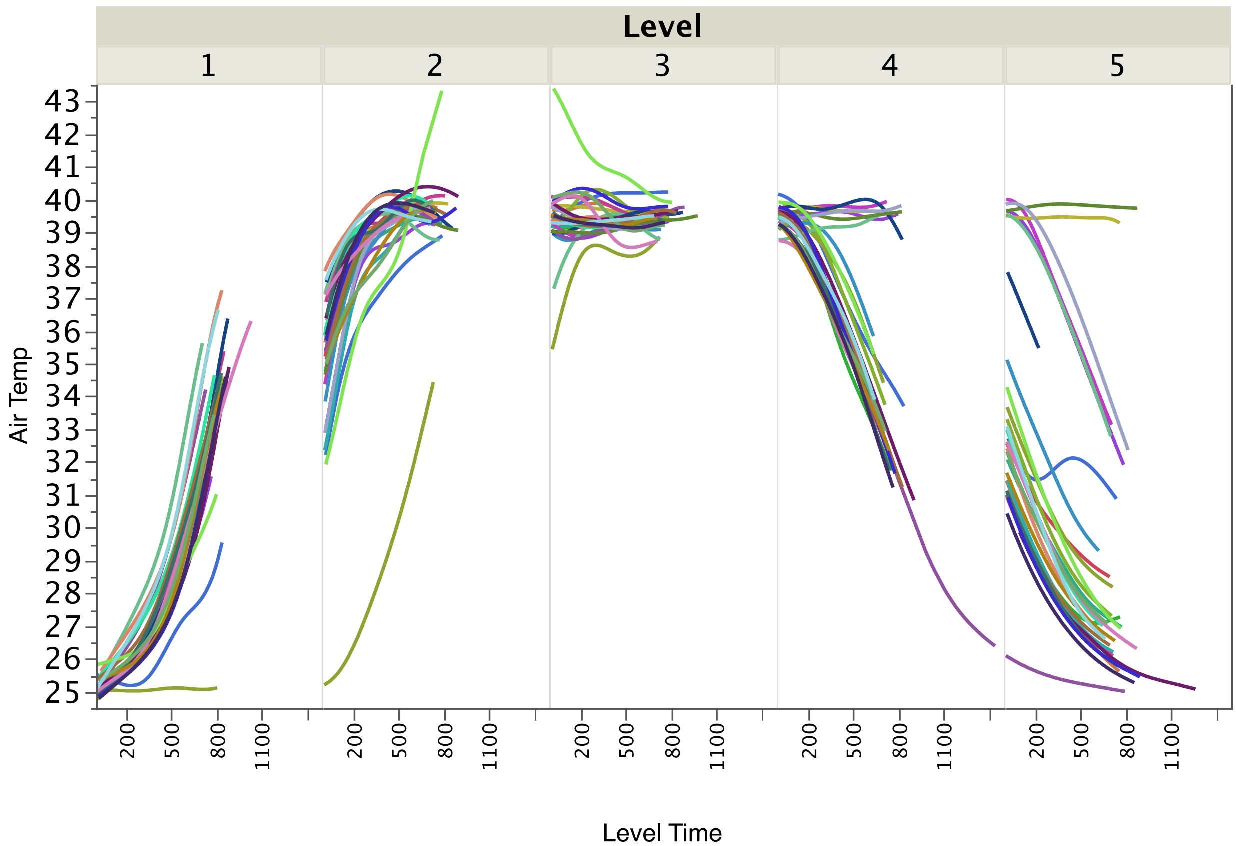

Figure 1. Air Temperature as a function of time in each level for each participant.

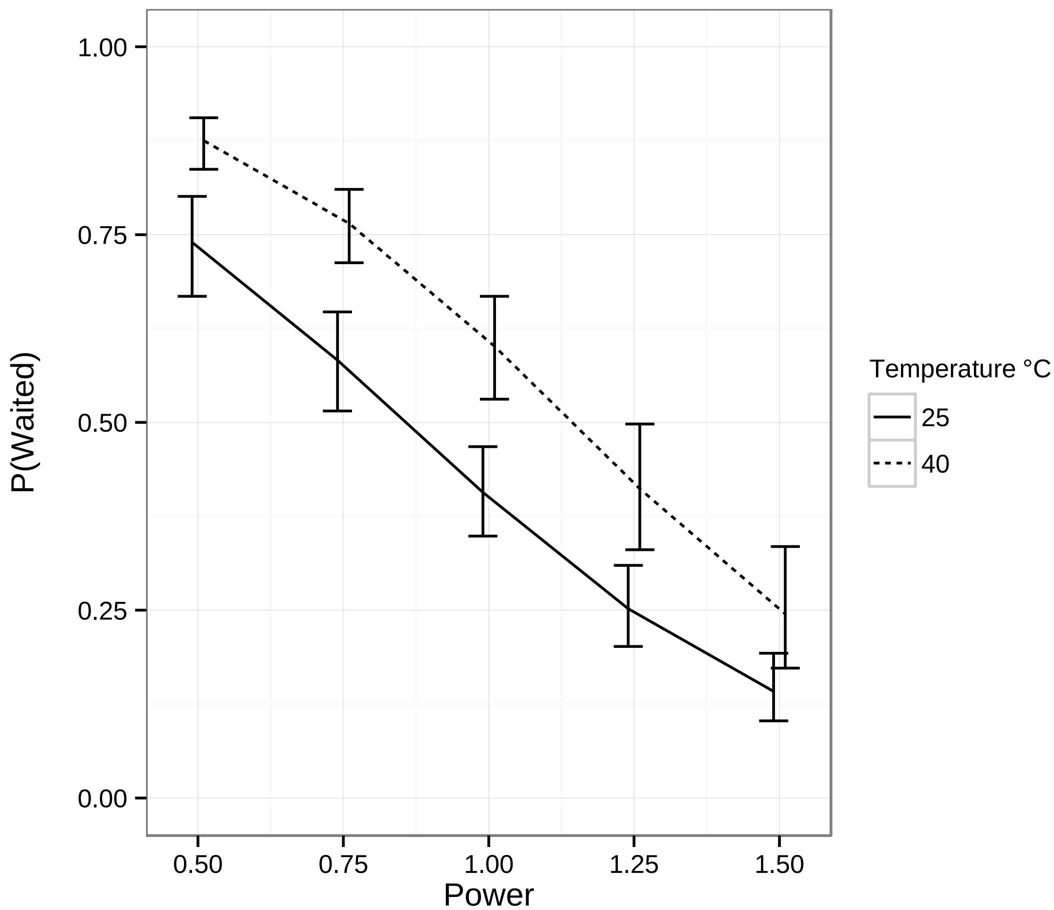

Figure 2. The predicted probability of waiting more than 5 s between shots as a function of the value of the power parameter (see Equation 1) at the two temperature extremes.

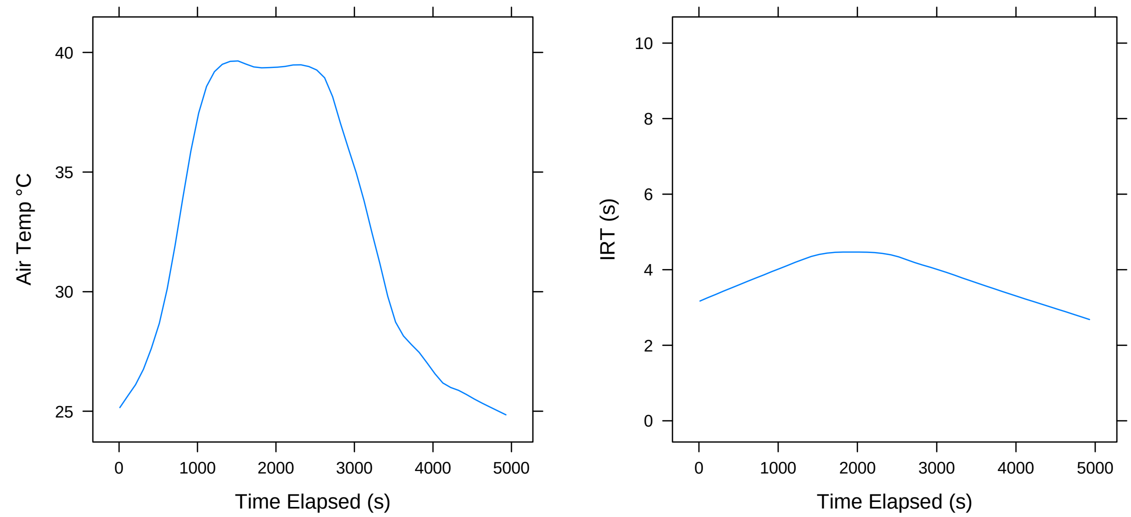

Figure 3. Left: Average air temperature as a function of time elapsed in the entire game (in seconds). Right: Average interresponse time (IRT) as a function of time elapsed.

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