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How to cite

FALK, Johanna Rebecca et al. Noise annoys—But personal choice can attenuate noise effects on cardiac response reflecting effort. In: Psychophysiology, 2023, p. e14502. doi: 10.1111/psyp.14502

This publication URL: https://archive-ouverte.unige.ch/unige:174401

Publication DOI: 10.1111/psyp.14502

Noise Annoys—But Personal Choice Can Attenuate Noise Effects on Cardiac Response Reflecting Effort

Johanna R. Falk[1,2], Peter M. Gollwitzer[3], Gabriele Oettingen[3], and Guido H.E. Gendolla[1,2]

[1] FPSE, Section of Psychology, University of Geneva, Switzerland

[2] Swiss Center for Affective Sciences, University of Geneva, Geneva, Switzerland

[3] New York University, New York, USA

Final accepted version of:

Falk, J.R., Gollwitzer, P.M., Oettingen, G., & Gendolla, G.H.E. (2023). Noise annoys-But personal choice can attenuate noise effects on cardiac response reflecting effort. *Psychophysiology*, Article e14502. Advance online publication. https://doi.org/10.1111/psyp.14502

Author Note

This research was supported by a grant from the Swiss National Science Foundation (SNF 100014_185348/1) awarded to Guido H.E. Gendolla. We thank Cheyenne Mauriello (Study 1) and Threcy De Rego (Study 2) for their help as hired experimenters.

The data, data coding, and data analysis code for the here reported studies are available on Yareta—the open access data archiving server of the University of Geneva: https://doi.org/10.26037/yareta:rpyueqjes5fa3a42jknukynpaq

Please address correspondence to Johanna Falk or Guido H.E. Gendolla, Geneva Motivation Lab, FPSE, Section of Psychology, University of Geneva, Bd. du Pont d'Arve 40, CH-1211 Geneva, Switzerland, or electronically to johanna.falk@unige.ch or guido.gendolla@unige.ch.

Abstract

Since *personal choice* fosters commitment and shields action execution against potentially conflicting influences, two laboratory experiments with university students ($N = 228$) tested whether engaging in action by personal choice vs. external assignment of task characteristics moderates the effect of irrelevant acoustic noise on cardiovascular responses reflecting effort. Participants who could personally choose the stimulus color of moderately difficult cognitive tasks were expected to be shielded against the irrelevant noise. By contrast, when the stimulus color was externally assigned, we predicted receptivity for the irrelevant noise to be high. As expected, in both experiments, participants in the assigned color condition showed stronger cardiac pre-ejection period reactivity during task performance when exposed to noise than when working in silence. On the contrary, participants who could choose the stimulus color were shielded against the noise effect on effort. These findings conceptually replicate and extend research on the action shielding effect by personal choice and hold practical implications for occupational health.

Keywords: cardiovascular response; effort; choice; noise; pre-ejection period; action shielding; volition.

Introduction

Extraneous noise is a primary example of an environmental stressor (Szalma & Hancock, 2011)—one of the main sources of annoyance at work (Becker, 1981; Sundstrom, 1986)—and has been linked to various harmful effects on well-being and health. Industrial work settings with high-intensity acoustic noise can have severe auditory health effects up to hearing loss (Kryer, 1970; Miller, 1974). Further noise effects comprise disturbance and physiological, motivational, and impaired performance (Evans & Johnson, 2000). A large body of research has investigated the relationship between noise and cognitive performance, indicating that irrelevant noise can break through selective attention and impair important cognitive functions (Banbury et al., 2001; Szalma & Hancock, 2011). However, the magnitude of these noise effects varies as a function of noise characteristics, the tasks to perform, and the performance measures used to assess it (see Banbury et al., 2001; Cohen & Weinstein, 1981; Smith, 1989 for reviews; Szalma & Hancock, 2011, for a meta-analytic synthesis). Overall, it is difficult to confidently predict the effects of noise on performance in specific situations, and the underpinning mechanisms are subject to diverging theoretical accounts (Cohen & Weinstein, 1981; Szalma & Hancock, 2011).

Considerably less work examined the role of effort—i.e., resource mobilization for action execution (Gendolla & Wright, 2009)—although theorizing and research suggest that individuals' adaptation to noise through compensatory effort may successfully counteract noise's deteriorating effects on performance: It has been theoretically argued and experimentally supported that individuals can cope with the distracting properties of noise during cognitive performance, but only when they mobilize additional compensational resources through psychophysiological activation (Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Hockey, 1997; Tafalla & Evans, 1997). The finding that individuals generally invest more effort into cognitive performance under noise exposure is supported by self-report measures and psychophysiological effort markers (Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Tafalla & Evans, 1997). Variance in compensatory effort may potentially account for discrepancies and varying effect sizes in the noise-performance literature, but especially effort-related responses in the cardiovascular system are of high relevance for occupational health. Individuals may pay psychophysiological costs for compensatory effort since cardiovascular reactivity has been identified as a key variable in the development of essential hypertension and cardiovascular disease (Baumann et al., 1973; Blascovich & Katkin, 1993; Krantz & Manuck, 1984; Light et al., 1992; Menkes et al., 1989; Steptoe & Ross, 1981; Treiber et al., 2003).

Hence, to prevent adverse health effects due to sustained cardiovascular activity, it is crucial to identify conditions in which individuals can continuously work productively while maintaining moderate cardiovascular activity. Based on the aforementioned studies, creating such conditions seems to be especially important in work settings where people are frequently exposed to irrelevant acoustic noise that cannot be prevented.

The Role of Action Shielding

Increasing the extent to which people can make personal choices—and thus have personal control over their work—has repeatedly been identified as important factor for improving various work- and health-related outcomes (e.g., mental health, sickness absence rates, self-rated performance; Bond & Bunce, 2001). Effects of personal choice have also been reported in the context of research and theorizing on volition: Intention formation has been associated with increased commitment (Bouzidi et al., 2022; Nenkov & Gollwitzer, 2012; Oettingen et al., 2001; Ryan & Deci, 2006), a heightened task focus (Kuhl, 1986), and a phenomenon called goal shielding (Gollwitzer, 1990).

Based on an action-shielding model (Gendolla et al., 2021), a recent series of studies on the effects of personal choice demonstrated that choice-based action shielding against unintended external affective influences applies to two important aspects of volition—effort intensity and persistence (Bouzidi & Gendolla, 2023a, Study 2; Falk et al., 2022a, 2022b; Framorando et al., 2023a, 2023b; Gendolla et al., 2021). These findings suggest that personal choice indeed leads to an action shielding process that protects action execution from distracting and potentially conflicting influences from the environment. Consequently, the way people engage in a task—by personal choice vs. external assignment—should moderate the impact of irrelevant noise effects in volition. Pointing in a similar direction, individuals who could choose the intensity of noise in a laboratory experiment experienced lower subjective and physiological arousal compared to others who could not choose (Lundberg & Frankenhaeuser, 1978). Research and theorizing on the action shielding effect has yet to be integrated with research on irrelevant noise effects on effort and its physiological signature. To address this, the present studies tested the dynamic relationship between personal choice, irrelevant noise, and mental effort.

Motivational Intensity Theory: A Theoretical Framework for Effort Intensity

The integration of research on irrelevant noise effects with the general psychological principles of resource mobilization allows for specific and context-dependent predictions about noise effects on responses in the cardiovascular system reflecting effort. According to the motivational intensity theory (Brehm & Self, 1989), individuals avoid investing more resources than necessary. In the context of tasks with fixed and clear difficulty, effort thus rises proportionally with experienced task demand as long as success is possible, and the required effort is justified. Following this principle, effort is low when a task is subjectively easy, moderate when the task feels moderately difficult, and high when the task is experienced as difficult but feasible. Only when task demand exceeds the person’s ability, or if the necessary effort is not justified by the importance of success, individuals should disengage and withdraw effort to avoid wasting their resources.

Over the last decades, these predictions have found ample empirical support through cardiovascular measures of effort (see Gendolla et al., 2012, 2019; Richter et al., 2016; Wright & Kirby, 2001, for reviews). Several variables have been identified that take effect on effort by influencing subjective task difficulty, such as conscious and implicit affect (Gendolla & Brinkmann, 2005; Gendolla, 2012; Gendolla, Brinkmann, et al., 2012; Gendolla & Richter, 2005, for overviews), or ability and fatigue (Wright, 1998; Wright & Barreto, 2012; Wright & Kirby, 2001; Wright & Stewart, 2012, for overviews). Based on previous research on irrelevant noise effects on resource mobilizations (e.g., Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Tafalla & Evans, 1997), we expect noise to take effect on effort through a similar mechanism: When working on a cognitive task and simultaneously being exposed to irrelevant noise, the noise should increase the perceived task demand during task performance and thereby effort—as long as the necessary effort is possible and justified.

Effort and Cardiovascular Response

Based on Wright's (1996) integration of motivational intensity theory (Brehm & Self, 1989) with the psychophysiological active coping approach (Obrist, 1981), effort intensity can be operationalized by indicators of beta-adrenergic sympathetic impact on the heart. The sympathetic innervation of the heart affects two main parameters of cardiac performance: The contraction pace and the contractile force of the heart muscle (Levick, 2010). Because the heart's pace depends on both the independent impacts of sympathetic and parasympathetic activity, heart rate (HR) is no highly reliable effort indicator. By contrast, the heart's contractile force directly depends on beta adrenergic sympathetic nervous system impact (Richter et al., 2016). Cardiac pre-ejection-period (PEP)—the time interval between ventricular depolarization onset and the opening of the aortic valve—is a direct indicator of myocardial contractile force (Berntson et al., 2004) and thus an ideal effort index (Kelsey, 2011). Stronger beta-adrenergic sympathetic impact results in shorter PEP.

Because of its link with cardiac contractile force, many earlier studies have also operationalized effort as performance-related changes in systolic blood pressure (SBP; the maximal vascular pressure between two consecutive heart beats, see Gendolla, Wright et al., 2012; Richter et al., 2016; Wright & Kirby, 2001, for reviews). SBP, and to a stronger degree diastolic blood pressure (DBP, the minimal vascular pressure between two consecutive heart beats), are also influenced by peripheral resistance in the vasculature, which is not systematically influenced by beta-adrenergic impact. However, although PEP is the purest indicator of beta-adrenergic sympathetic impact and thus the most reliable and valid cardiovascular measure of effort (Kelsey, 2011; Richter et al., 2008; Wright, 1996), it should always be assessed together with HR and blood pressure to monitor possible effects of cardiac preload (ventricular filling) and vascular afterload (arterial pressure) on PEP (Sherwood et al., 1990).

The Present Studies

Building on the action shielding model (Gendolla et al., 2021) and on the research supporting it for the effects of music on effort-related cardiovascular responses (Falk et al., 2022a, 2022b), we presumed that providing personal choice should increase commitment and task focus, and shield action execution against extraneous influences, including task irrelevant acoustic noise. However, when a task and its characteristics are externally assigned, commitment and task focus should be weaker, and receptivity for extraneous influences should be higher: Here, during task performance irrelevant noise should increase subjective task demand and thus effort.

We ran two laboratory experiments to test our hypothesis. In both studies, half the participants could personally choose one of four colors in which the stimuli of a moderately difficult short-term memory task would be presented. The other half of the participants performed the task with an assigned stimulus color, corresponding to that chosen by their yoked participant in the Chosen Color condition. During task performance half of the participants in each group were continuously exposed to an irrelevant and unpleasant external noise—the sound of a drill. The other half worked in silence. For our moderately difficult tasks, we predicted relatively strong effort-related cardiovascular response—especially PEP—in the Assigned Color/Noise condition, and moderate reactivity in the other three conditions (Assigned Color/Silence, Chosen Color/Noise, Chosen Color/Silence).

We also assessed task performance in terms of response speed and accuracy. However, given that the relationship between effort (behavioral input) and performance (behavioral output) is more complex than simply linear (Locke & Latham, 1990), we did not formulate *a priori* hypotheses for task performance effects.

Experiment 1: Memory Task – Numbers

For our first study, we tested the combined effect of noise and choice on effort in the context of a moderately difficult short-term memory task: Participants had to decide, for each trial, whether two successively presented number series were identical or not. We predicted a 3:1 pattern of cardiovascular reactivity (especially PEP), with stronger responses in the Assigned Color/Noise condition than in the other three conditions because noise should increase subjective task demand during performance, but only in the condition where participants were assigned to the task characteristics. Participants in the chosen color condition should be shielded against the noise effect on effort, leading to relatively weak cardiovascular responses in both the noise and silence conditions. This is because without the background noise or when being shielded against noise, the moderately difficult cognitive task should only necessitate moderate effort, according to the principles of motivational intensity theory (Brehm & Self, 1989), and as demonstrated in previous action shielding studies with music stimulations in moderately difficult tasks (Falk et al., 2022a; Gendolla et al., 2021, Study 2).

Methods

Participants and Design

Previous studies manipulating external acoustic music stimulation and a comparable choice manipulation found significant medium-sized effects on PEP reactivity measures with samples of 20-31 participants per condition (Falk et al., 2022a, 2022b; Gendolla et al., 2021). To have a comparable sample size, we aimed at collecting data of 30 participants per condition. Thus, 121 university students were randomly assigned to our 2 (Choice) x 2 (Noise) between-persons experimental design. Due to electrode detachments and other technical issues, data sets of 9 participants could not be analyzed. There were two outliers for PEP reactivity (> 3 *SDs* than the condition *M*s) who were excluded from the analysis of this measure. Thus, the final sample consisted of $N = 112$ ($N = 110$ for PEP) participants (83 women, 29 men; average age 21 years) with the following numbers of participants in the four conditions: Chosen Color/Silence (29 participants), Chosen Color/Noise (26 participants), Assigned Color/Silence (28 participants), Assigned Color/Noise (29 participants). The gender distributions were balanced between the conditions.[1] According to a sensitivity analysis run with G*power (Faul et al., 2007), our sample

[1] Chosen Color/Silence (19 women/7 men), Chosen Color/Noise (19 women/7 men), Assigned Color/Silence (21 women/7 men), and Assigned Color/Noise (21 women/8 men). Not surprisingly, a chi-square test of these frequency distributions was nowhere near significance ($p = .99$).

size was sufficient to detect significant *a priori* contrast effects as well as ANOVA main and interaction effects of a medium size with 80% power in our 2 x 2 factorial design.

Physiological Measures

We used a Cardioscreen 1000 system (medis, Imenau, Germany) to noninvasively record (sampling rate 1000 Hz) electrocardiogram (ECG) and thoracic impedance (ICG) signals, from which we derived cardiac PEP and HR. Two pairs of single-use electrodes (Ag/AgCI; medis, Imenau, Germany) were attached: One dual sensor to the left side of the base of the participants' neck, and two single sensors on the participants' chest (left middle axillary line at the height of the xiphoid). We used BlueBox 2.V1.22 software (Richter, 2010) for data processing. R-peaks were automatically identified using a threshold peak detection algorithm and visually confirmed, allowing to determine HR (in beats/min). The first derivative of the change in thoracic impedance was calculated, and the resulting dZ/dt signal (low-pass filtered at 50 Hz) was ensemble averaged over 1-min periods, based on the detected R-peaks. B-point location was estimated based on the RZ interval of valid heart beat cycles (Lozano et al., 2007), visually checked, and manually corrected (Sherwood et al., 1990), to determine PEP (in ms; interval between R-onset and B-point; Berntson et al., 2004). The signal inspection and eventual B-point correction took place on the raw data basis before the statistical analyses, blind of the experimental conditions, and without knowledge of condition *M*s.

Systolic (SBP) and diastolic blood pressure (DBP; both in mmHg) were oscillometrically assessed in 1-min intervals with a Dinamap ProCare monitor (GE Healthcare, Milwaukee, WI). A blood pressure cuff was placed over the brachial artery above the elbow of participants' non-dominant arm. The cuff inflated automatically in 1-min intervals and assessed values were stored by the monitor. For researchers interested in more detailed hemodynamic responses that were unrelated to our hypotheses, analyses of cardiac output and total peripheral resistance are accessible in the Online Supplementary Material (OSM).

Procedure

All procedures and measures were approved by the local Ethics Committee. The experiment was run with E-Prime 3.0 (Psychology Software Tools, Sharpsburg, PA) and advertised as a 30-min study on cardiovascular activity during a cognitive task. To prevent biased behavior, the real purpose of the experiment was not communicated. The experimenter was hired and unaware of both the hypotheses and the experimental conditions. Participants were recruited through flyers distributed in the university buildings and through the university’s internal online job portal. Inclusion criteria were the following: Fluency in the French language, being in generally good health (no chronic illnesses, pacemaker, use of antidepressants, or other medications that may affect the cardiovascular system), and being at least 18 years old. Psychology students were not allowed to participate. To control for caffeine effects on the cardiovascular system (see Grant et al., 2018), participants were instructed not to consume any caffeine on the testing day. Additionally, participants were instructed not to consume heavy meals 2 hours prior to testing to prevent digestion effects on the cardiovascular system.

Upon arrival, participants were welcomed, seated in a comfortable chair in front of a computer, and gave written informed consent. The experimenter attached the physiological sensors, started the experimental software, and went to an adjacent control room. After a brief explanation of the general procedure, participants were instructed to relax and maintain the same body position throughout the subsequent relaxation phase. Cardiovascular baseline values were assessed during the presentation of a hedonically neutral 8-min long film about trees. Next, the task instructions of the moderately difficult cognitive task (adapted from Bijleveld, 2018) were displayed: “For 5 minutes, you will perform a concentration task. A trial goes like this: A first series of 6 numbers is presented, followed by a series of 6 letters, and then followed by a second series of 6 numbers. Your task is to decide, for each trial, whether the first and second number series are identical or not. When the two series are identical, press the GREEN button. When the two series are not identical, press the RED button. Please answer correctly and as quickly as possible." Additionally, participants were provided with two examples: One example for an identical trial and one example for a non-identical trial (Identical Trial: 581643 → GHQIUR → 581643; Non-identical Trial: 294567 → GHQIUR → 293567). Then, all participant performed 5 practice trials. During that training phase, feedback indicated whether the participants' responses were correct or wrong. Whenever the participant did not respond within 2 sec, the message "please answer faster" appeared.

Next, participants in the Chosen Color condition learned that they could now, based on their preference, choose one of 4 colors in which the stimuli of the upcoming cognitive task would be displayed. To give participants a reason for their choice, they read: "Current research results show that the possibility of choosing a stimulus color has a positive effect on task performance". After participants had pressed "enter" to continue, examples of the available colors (red, blue, green, yellow) were provided. The next screen then asked participants to deliberate for 1-min on the question "Which stimulus color do you prefer?". Participants started by pressing "enter". After 1 min, they were asked to indicate their choice by pressing one of the color-corresponding keys indicated on the display. Next, the chosen color and the question "Are you sure about your choice?" were displayed to assure their commitment to the chosen color. If the participant pressed the green key for "yes", the procedure continued; if the participant pressed the red key for "no", the stimuli colors were presented once again, and participants indicated their choice again. The procedure continued once the personal color choice was confirmed.

In the Assigned Color condition, participants were assigned to the color that was previously chosen by their yoked participant in the Chosen Color condition. As an example, if the yoked participant previously chose the stimulus color blue, participants read “Current research results show a positive effect on task performance when the task stimuli are displayed in blue”. That way, both the chosen and the assigned color had the same ostensible effect. To further create parallel Chosen and Assigned Color conditions, Assigned Color participants took a 1-min break.[2]

Then, task instructions and the reminder to maintain the same body posture were displayed again, and participants in the Noise condition were informed about the presentation of an irrelevant acoustic stimulation during the upcoming main task. Participants in the Silence condition were informed that no acoustic stimulation would be present during the upcoming main task. There was also a reminder given in which color the stimuli would be presented in the main task: Participants in the Choice condition read “Following your choice, the letters will be presented in blue/green/yellow/red”, respectively. Participants in the Assignment condition only read “The letters will be presented in blue/green/yellow/red”, respectively.

All participants worked on the same cognitive task (only the stimulus colors could differ) and were presented with 37 task trials. The task took 5 min, and in total, the trials contained 18 identical and 19 non-identical number series. Trials started with a fixation cross (1 sec), followed by a series of 6 numbers (1 sec), a series of 6 letters (1.5 sec), and a second series of 6 numbers (max. 2 sec). The second number series was either identical or non-identical with the first number

[2] We had deliberately decided not to include a choice manipulation check in this experiment. The same color choice induction has been successfully used before, where a manipulation check (“To what extent could you decide on the characteristics of the task?”) revealed highly significant and strong effects on participants’ feelings of having control over the characteristics of the task they worked on (Bouzidi & Gendolla, 2023a; Bouzidi et al., 2022; Falk et al., 2022). However, including a choice manipulation question might alert participants in the assigned task characteristics condition—they could perceive the manipulation check question as odd and realize that other participants could choose, which may influence their subsequent behavior. Moreover, we believe that our specific choice manipulation does not necessarily require a verbal manipulation check since participants experienced the consequence of their choice during the task: The stimuli appeared in the chosen color.

series and appeared until a response button was pressed. When no response was given within 2 sec, the feedback "please answer faster" was displayed for 2 sec. If the response button was pressed in time, the feedback response registered was displayed for 4 sec minus the reaction time. That way, all trials had the same time length in all conditions. The intertrial interval randomly varied between 550 ms and 1 sec.

During task performance, participants in the Noise condition were exposed to the noise of a drill, whereas participants in the Silence condition completed the task without any acoustic stimulation. The intensity of the drill-noise dynamically varied over the 5-min period, with an average volume of 60 dB and the highest peaks reaching about 65 dB. The irrelevant noise was presented through two speakers, placed about 30 cm behind the participant's chair. We deliberately decided not to use headphones because these could have been removed by the participant during the experimental procedure. Cardiovascular activity was assessed during the entire main task.

After the task, participants rated task difficulty ("To what extend did you find the task demanding?") on a scale ranging from 1 *(not at all)* to 7 *(very difficult)*. They also rated the acoustic environment during the task performance ("How did you perceive the acoustic environment?") on a scale going from 1 *(not unpleasant)* to 7 *(very unpleasant)*. Next, participants answered additional questions about their gender, mother tongue, French language proficiency, and medication use. The experiment ended with a debriefing session, the payment of the 10 Swiss Francs (about 10 USD) for participation, and the possibility to discuss one's personal experience of the procedure with the experimenter. Importantly, no participant guessed the purpose of the study.

Data Analysis

We performed *a priori* contrast analyses to test our expected 3:1 interaction pattern with relatively strong sympathetically mediated cardiovascular responses (especially PEP) in the Assigned Color/Noise condition (contrast weight +3) and weaker reactivity in the other three conditions (contrast weights -1). *A priori* contrasts are the most powerful and thus appropriate statistical tool to test hypotheses about predicted patterns of means (Rosenthal & Rosnew, 1985; Wilkinson & The Task Force on Statitical Infercene of APA, 1999). Measures for which we did not specify theory-based predictions were analyzed with conventional exploratory 2 (Choice) x 2 (Noise) between persons ANOVAs.

Results and Discussion

Cardiovascular Baselines

We had *a priori* decided to constitute baseline scores by averaging cardiovascular values of the last 3 min of the habituation period. We did so to comply with the recommendation to average at least three blood pressure measures (Shapiro et al., 1996) and because cardiovascular baseline values generally become stable towards the end of a habituation period.

Table 1
Means and Standard Errors (in parentheses) of the Cardiovascular Baseline Values.

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
PEP	97.18 (2.02)	98.55 (2.10)	97.33 (1.60)	96.79 (2.06)
SBP	100.67 (1.60)	103.31 (1.65)	102.64 (1.63)	103.29 (1.61)
DBP	57.71 (0.97)	57.55 (0.79)	58.08 (0.87)	58.29 (0.97)
HR	77.52 (2.24)	71.97 (1.69)	71.39 (1.76)	73.72 (1.82)

Note. PEP = pre-ejection period (in ms), SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). $N = 112$ for SBP, DBP, HR; $N = 110$ for PEP.

The cardiovascular measures showed high internal consistency during that period (McDonald's ωs ≥ .946). Cell means and standard errors appear in Table 1. Preliminary 2 (Choice) x 2 (Noise) ANOVAs revealed no significant baseline differences between the later conditions (*ps* ≥ .254).[3]

Cardiovascular Reactivity

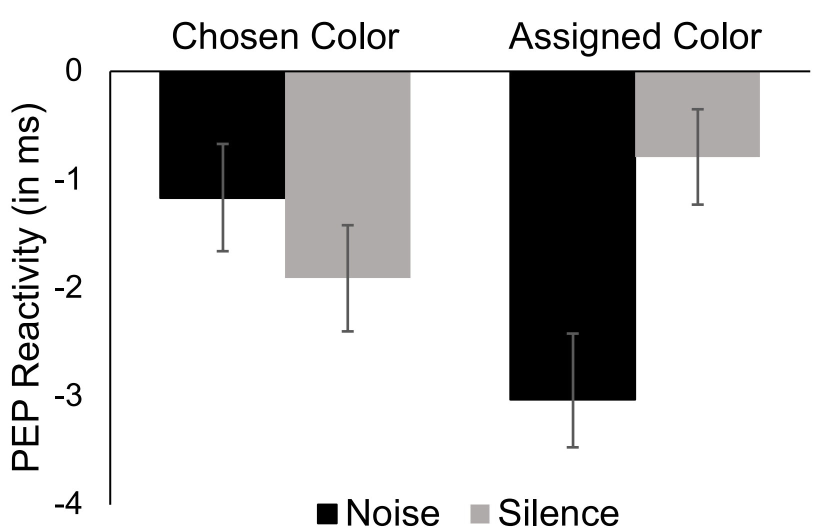
Descriptive statistics of the cardiovascular activity values during task performance are reported in the Online Supplementary Material. We created cardiovascular reactivity scores (Llabre et al., 1991) by subtracting the baseline values from the five 1-min values of PEP, HR, SBP, and DBP that were assessed during task performance. The five change scores for each measure showed high internal consistency (McDonald's ω*s* αs ≥ .921) and were averaged. Preliminary analyses of covariance (ANCOVAs) of the averaged cardiovascular reactivity scores with the respective baseline scores as covariate found no significant associations with the baseline scores of PEP, SBP, DBP, or HR (*ps* ≥ .298).

PEP Reactivity. As reported in the OSM, PEP reacted significantly during task performance in general and especially in the Assigned Color/Noise condition. Most relevant and in support of our hypothesis, our theory-based *a priori* contrast for PEP reactivity—our primary effort measure—was significant and of medium size, $F(1, 106) = 8.73$, $p = .004$, $\eta^2 = 0.08$. As depicted in Figure 1, the PEP responses showed the predicted 3:1 pattern (note that decreases in PEP are reflecting increases in beta-adrenergic sympathetic impact).

[3] The 3:1 contrast that tested our predictions about cardiovascular reactivity was not significant for any of the cardiovascular baseline scores ($p \geq .560$). For readers interested in gender differences in cardiovascular activity, we compared the baseline values of women and men with *t*-tests (including gender in three-factorial ANOVAs was no option because there were far more women than men in our sample). The analyses revealed significant gender differences for baseline values of SBP, $t(110) = 7.93$, $p < .001$, $\eta^2 = 0.36$, due to higher SBP for men ($M = 111.11$, $SE = 1.47$) than for women ($M = 99.43$, $SE = 0.71$). No other cardiovascular baseline values showed significant gender differences (*p*s ≥ .079). Further, gender had no significant effects on cardiovascular reactivity (*p*s ≥ .145).

Additional directed and thus one-tailed cell contrasts revealed that PEP reactivity in the Assigned Color/Noise condition (*M* = -3.03, *SE* = 0.61) was significantly stronger than in the Assigned Color/Silence condition (*M* = -0.79, *SE* = 0.44), $t(106) = 3.07$, $p = .002$, $\eta^2 = 0.08$, and—most relevant for the predicted shielding effect—the Chosen Color/Noise (*M* = -1.17, *SE* = 0.50) condition, $t(106) = 2.53$, $p = .001$, $\eta^2 = 0.06$. The difference between the Assigned Color/Noise and the Chosen Color/Silence (*M* = -1.91, *SE* = 0.49) conditions was in the expected direction but did not reach significance ($p = .061$). Moreover, cell contrasts between the Chosen Color/Silence, Chosen Color/Noise, and Assigned Color/Silence conditions did not reveal any significant differences between the conditions ($ps \geq .133$).

Figure 1. Cell means and ±1 standard errors underlying the combined effect of stimulus color choice and noise on cardiac pre-ejection period (PEP) reactivity. Shorter PEP reflects stronger beta-adrenergic sympathetic impact.



SBP, DBP, and HR Reactivity. Cell means and standard errors appear in Table 2. The *a priori* contrasts for the responses of HR, SBP, and DBP were not significant, $Fs(1, 108) \leq 1.44$, $ps \geq .233$, although the response pattern of HR largely corresponds to the 3:1 pattern.

Table 2
Means and Standard Errors (in parentheses) of blood pressure and heart rate reactivity scores (Experiment 1).

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
SBP	5.74 (0.91)	4.36 (1.00)	4.35 (0.68)	4.13 (0.79)
DBP	3.30 (0.60)	3.39 (0.64)	4.88 (0.79)	3.45 (0.56)
HR	4.03 (0.75)	3.46 (0.78)	2.68 (0.58)	4.32 (0.61)

Note. SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). $N = 112$ for all measures.

Task Performance

Overall, participants made 83.64% ($SE = 0.96$) correct responses with a mean reaction time of 956.95 ms ($SE = 14.01$) in correct trials. The relatively high response accuracy supports our intention to let participants work on a relatively easy task. A 2 (Choice) x 2 (Noise) ANOVA of response accuracy revealed no Choice or Noise main effects ($p \geq .426$), but a significant Choice x Noise interaction, $F(1, 108) = 6.73$, $p = .011$, $\eta^2 = .06$. Cell means and standard errors appear in Table 3.

Table 3
Means and Standard Errors (in parentheses) of Accuracy and Reaction Times of correct trials.

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
ACC	79.89 (2.05)	86.07 (2.00)	86.25 (1.47)	82.70 (1.90)
RT	977.17 (27.05)	959.47 (30.50)	950.67 (32.95)	940.51 (22.16)

Note. ACC = Accuracy (percentage of correct responses), RT = Reaction Time (in ms). $N = 112$ for all measures.

Cell comparisons with LSD *post hoc* tests found that participants in the Chosen Color/Noise condition made significantly more correct responses than participants in the Chosen Color/Silence condition ($p = .023$, $\eta^2 = 0.05$). Further, participants in the Chosen Color/Silence condition showed significantly fewer correct responses than participants in the Assigned Color/Silence condition ($p = .017$, $\eta^2 = 0.05$). A 2 (Choice) x 2 (Noise) ANOVA of the reaction times for correct responses revealed no significant effects ($ps \geq .424$). Cell means and standard errors also appear in Table 3.

Verbal Measures

Noise. A 2 (Choice) x 2 (Noise) ANOVA on the subjective noise ratings revealed a strong significant Noise main effect, $F(1, 108) = 81.53$, $p < .001$, $\eta^2 = 0.57$. Participants in the Noise condition ($M = 4.96$, $SE = 0.19$) rated the acoustic environment as significantly more unpleasant than those in the Silence condition ($M = 2.51$, $SE = 0.20$). Other effects were not significant ($ps \geq .127$). Moreover, in the Noise condition, the ratings were significantly higher than the scale's midpoint, $t(54) = 7.68$, $p < .001$, $\eta^2 = 0.52$. By contrast, in the Silence condition, the ratings were significantly lower than the scale's midpoint, $t(56) = 5.07$, $p < .001$, $\eta^2 = 0.31$. Altogether, this supports the assumption that we succeeded in creating an aversive noise stimulation.

Difficulty. A 2 (Choice) x 2 (Noise) ANOVA on the post task difficulty ratings revealed no significant effects (*ps* ≥ .139). Generally, rated difficulty (M = 3.84, SE = 0.14) was not significantly different from the scale's midpoint according to a one-sample t-test (p = .592). This suggests that the task was, as intended, perceived as moderately difficult by the participants.

Interim Conclusions

The main result of this study was the significant *a priori* 3:1 pattern of cardiac pre-ejection period responses during the task, our primary measure of effort intensity. Participants in the assigned task characteristics condition showed stronger cardiac PEP responses when they were exposed to irrelevant noise during performance of the moderately difficult task than those who worked in silence. Importantly, when participants could personally choose one of four colors in which the task stimuli would be presented, cardiac PEP reactivity was moderately high and showed no evidence of a noise influence. We interpret our findings as support for our hypothesis that personal choice can shield against noise effects on effort-related responses in the cardiovascular system. However, although the *a priori* contrast was significant, the cell difference between the Assigned Color/Noise and the Chosen Color/Silence conditions was not. Therefore, we run a conceptual replication study.

Experiment 2: Memory Task – Letters

Our second study aimed to replicate the results of Study 1 and to provide additional and more conclusive evidence for our *action shielding* hypothesis. To generalize the combined effect of noise and the choice of task characteristics on effort intensity, we administered a different moderately difficult short-term memory task: Participants had to memorize and correctly report four letter series. Otherwise we used the same materials and procedure as in Study 1.

Method

Participants and Design

We once again aimed at collecting data of 30 participants per condition and randomly assigned 121 university students to our 2 (Choice) x 2 (Noise) between-persons experimental design. This time, due to electrode detachments and other technical issues, data sets of 5 participants could not be analyzed. There was one outlier for the reactivity scores of PEP, SBP, HR, and response speed (> 3 *SDs* than the condition *M*) who was excluded from the analyses for the respective measures. Thus, the final sample consisted of $N = 116$ ($N = 115$ for PEP, SBP, HR, and response speed) participants (96 women, 20 men; average age 22 years) with the following numbers of participants in the four conditions: Chosen Color/Silence (29 participants), Chosen Color/Noise (30 participants), Assigned Color/Silence (26 participants), Assigned Color/Noise (31 participants). The gender distributions were similar in the four conditions.[4]

Procedure

The experimenter was again hired and unaware of both the predictions and the experimental conditions. The initial greeting, explanations, and cardiovascular baseline measures were identical to Experiment 1. Then, the task instructions for the moderately difficult memory task were displayed: "For 5 minutes, you will perform a memory task. Four series of seven letters are presented. Each letter series will be presented for 75 sec, then the next letter series will be presented. Your task is to memorize all letters of the four seven-letter series and to report them in the correct order at the end of the experiment." Next, as in Experiment 1, participants in the Chosen Color condition learned that they could now, based on their preference, choose one of 4

[4] Chosen Color/Silence (25 women/4 men), Chosen Color/Noise (24 women/6 men), Assigned Color/Silence (22 women/4 men), and Assigned Color/Noise (25 women/6 men). A chi-square test of these frequency distributions was nowhere near significance ($p = .91$).

colors in which the stimuli of the upcoming cognitive task would be displayed. In the Assigned Color condition, participants were assigned to the color that was previously chosen by their yoked participant in the Chosen Color condition.

The task started with the presentation of the first letter series (75 sec), followed by the second series (75 sec), and so on. Participants in the Noise condition were exposed to the same noise of a drill during the task as in Experiment 1, whereas participants in the Silence condition completed the task without any acoustic stimulation. After the task, participants rated task difficulty ("To what extend did you find the task demanding?") on a scale from 1 *(not at all)* to 100 *(very difficult)* using a slider. They also rated the acoustic environment during the task performance ("How did you perceive the acoustic environment?") on a scale reaching from 1 *(not unpleasant)* to 100 *(very unpleasant)*. Next, participants answered again biographical questions and were then asked to write down all letters they had memorized in the correct order of their appearance. The procedure finished with a debriefing and the remuneration. Again, no participant guessed the purpose of the study.

Results and Discussion

The calculation of cardiovascular indices and the data analyses were done as in Experiment 1.

Cardiovascular Baselines

The cardiovascular measures taken during the last three minutes of the habituation period showed again high internal consistency and were averaged (McDonald's ω*s*'s *αs* $\geq .946$). Cell means and standard errors appear in Table 4. Preliminary 2 (Choice) x 2 (Noise) ANOVAs revealed no significant baseline differences between conditions (*ps* $\geq .089$).[5]

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[5] The 3:1 contrast that tested our predictions about cardiovascular reactivity was not significant for any of the cardiovascular baseline scores ($p \geq .069$). For readers interested in gender differences in cardiovascular activity, we

Table 4
Means and Standard Errors (in parentheses) of the Cardiovascular Baseline Values.

	Chosen Color		Assigned Color	
	Silence	**Noise**	**Silence**	**Noise**
PEP	96.85 (2.3)	98.70 (2.48)	98.00 (2.51)	100.39 (1.53)
SBP	103.70 (1.46)	103.08 (1.74)	101.04 (1.83)	103.59 (2.10)
DBP	57.87 (0.90)	57.99 (0.77)	57.38 (0.83)	58.30 (0.88)
HR	79.52 (1.87)	75.20 (1.92)	75.85 (2.41)	72.71 (1.86)

Note. PEP = pre-ejection period (in ms), SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). N = 115 for all measures except for DBP N = 116.

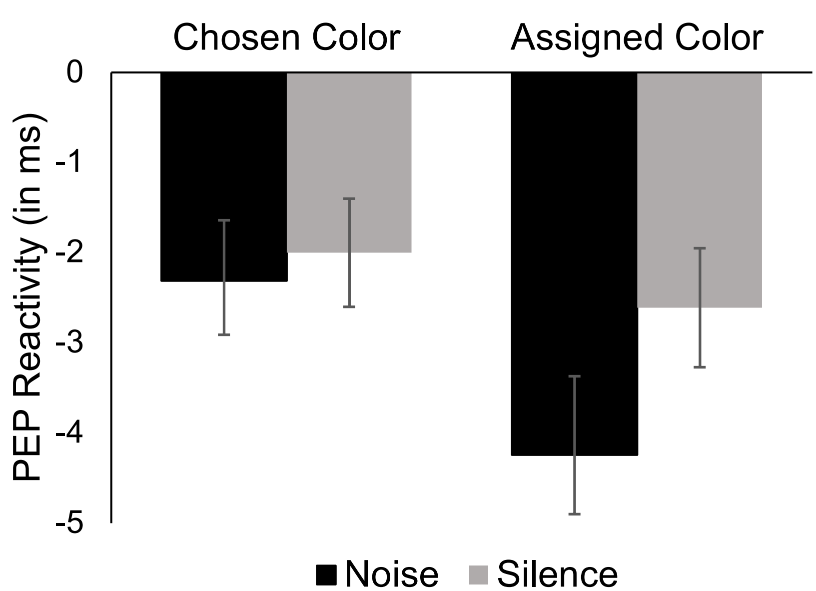
Cardiovascular Reactivity

Descriptive statistics of the raw cardiovascular activity values during task performance are reported in the Online Supplementary Material. The five 1-min change scores for each measure showed high internal consistency (McDonald's ω*s* αs ≥ .892). Preliminary analyses of covariance (ANCOVAs) of the averaged cardiovascular reactivity scores with the respective baseline scores as covariate only found a significant association between the HR baseline and reactivity scores, $F(1, 110) = 5.47$, $p = .021$, $\eta^2 = 0.05$. Therefore, we analyzed baseline-adjusted reactivity scores of HR to prevent possible carryover or an initial values effect. No significant associations emerged between the baseline and reactivity scores of PEP, SBP, and DBP (*ps* ≥ .059).

compared the baseline values of women and men with *t*-tests (including gender in three-factorial ANOVAs was again no option because there were far more women than men in our sample). The analyses revealed significant gender differences for baseline values of SBP $t(113) = 4.67$, $p < .001$, $\eta^2 = 0.16$, due to higher SBP for men (M = 111.30, SE = 2.14) than for women (M = 101.14, SE = 0.89). No other cardiovascular measures showed significant gender differences for baseline values (*p*s ≥ .433). Furthermore, gender had no significant effect on cardiovascular reactivity (*p*s ≥ .052).

PEP Reactivity. As reported in the OSM, PEP significantly reacted in general and especially in the Assigned Color/Noise condition. Most relevant, our theory-based *a priori* contrast for PEP reactivity—our primary effort-related measure—was again significant, $F(1, 111) = 5.66$, $p = .019$, $\eta^2 = 0.05$, supporting our hypothesis. As depicted in Figure 2, the PEP responses showed the predicted 3:1 pattern (note that decreases in PEP are reflecting increases in beta-adrenergic sympathetic impact).

Figure 2. Cell means and ±1 standard errors underlying the combined effect of stimulus color choice and noise on cardiac pre-ejection period (PEP) reactivity. Shorter PEP reflects stronger beta-adrenergic sympathetic impact.



Additional one-tailed cell contrasts revealed that PEP reactivity in the Assigned Color/Noise condition ($M = -4.24$, $SE = 0.87$) was significantly stronger than in the Chosen Color/Noise condition ($M = -2.31$, $SE = 0.67$), $t(111) = 1.95$, $p = .027$, $\eta^2 = 0.03$, which is most relevant to the predicted shielding effect, and the Chosen Color/Silence condition ($M = -2.00$, $SE = 0.60$), t(111) = 2.23, $p = .014$, $\eta^2 = 0.04$. The difference between the Assigned Color/Noise and the Assigned Color/Silence (*M* = -2.61, *SE* = 0.66) conditions was in the expected direction but not significant ($p = .059$). In line with our predicted pattern, the differences between the Chosen Color/Silence, Chosen Color/Noise, and Assigned Color/Silence conditions were not significant ($ps \geq .557$).

HR Reactivity. The 3:1 *a priori* contrast was also significant for baseline-adjusted HR reactivity, $F(1, 111) = 7.43$, $p = .007$, $\eta^2 = 0.06$. As depicted in Table 5, the HR responses showed the predicted 3:1 pattern.

The additional cell contrast between the Assigned Color/Noise condition and the Assigned Color/Silence condition was significant: HR reactivity in the Assigned Color/Noise condition was significantly stronger than in the Assigned Color/Silence condition, $t(111) = 1.86$, $p = .033$, $\eta^2 = 0.03$. Reactivity in the Assigned Color/Noise condition was not significantly stronger than in the Chosen Color/Noise condition ($p = .082$). HR reactivity in the Assigned Color/Noise condition was significantly stronger than in the Chosen Color/Silence condition, $t(111) = 3.34$, $p = .001$, $\eta^2 = 0.09$. In line with the predicted pattern, the differences between the Chosen Color/Silence, Chosen Color/Noise, and Assigned Color/Silence conditions were not significant ($ps \geq .059$).

SBP and DBP Reactivity. Cell means and standard errors appear in Table 5. The 3:1 *a priori* contrast was not significant for the SBP responses ($p = .143$) but significant for DBP reactivity, $F(1, 112) = 11.94$, $p = .001$, $\eta^2 = 0.10$. As depicted in Table 5, DBP reactivity followed the predicted 3:1 pattern. Additional cell contrasts revealed that DBP reactivity in the Assigned Color/Noise condition was significantly stronger than in the Assigned Color/Silence condition, $t(112) = 3.13$, $p < .001$, $\eta^2 = 0.08$, and the Chosen Color/Silence condition, $t(112) = 3.65$, $p = .001$, $\eta^2 = 0.11$, while the difference to the Chosen Color/Noise condition fell short of significance ($p = .061$). Moreover, reactivity in the Chosen Color/Noise condition was significantly stronger than in the Chosen Color/Silence condition, $t(112) = 2.09$, $p = .039$, $\eta^2 = 0.04$. The comparisons between the Chosen Color/Silence and Assigned Color/Silence condition, as well as the comparison between the Chosen Color/Noise and Assigned Color/Silence conditions were not significant (ps > .108).

Table 5
Means and Standard Errors (in parentheses) of blood pressure and heart rate reactivity scores (Experiment 2).

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
SBP	3.99 (0.67)	6.32 (0.92)	4.19 (0.73)	6.12 (0.71)
DBP	2.51 (0.51)	4.34 (0.78)	2.88 (0.55)	5.69 (0.59)
HR	3.59 (0.63)	5.97 (0.86)	5.34 (0.98)	7.69 (1.02)

Note. SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). $N = 115$ for SBP and HR, $N = 116$ for DBP.

Task Performance

Cell means and standard errors appear in Table 6. Overall, participants correctly remembered $M = 72.17\%$ ($SE = 2.19$) of the presented letters (a remembered letter only counted as correct when it was correctly indicated for the respective letter series and its position). This relatively high number of correctly remembered letters speaks for our aim to create a relatively easy task. We also analyzed the speed (in ms) with which participants entered the remembered letters. Overall, participants took 80018.16 ms ($SE = 4221.43$) to type in and confirm all letter series. A 2 (Choice) x 2 (Noise) ANOVA of the percentage of correctly remembered letters revealed no significant effects (ps > .408). An ANOVA of response speed found that participants in the Noise condition ($M = 87997.73$, $SE = 5763.84$) tended to respond more slowly than those in the Silence condition (M = 72038.58, SE = 6142.09, $F(1, 111) = 3.59$, p = .061, $\eta^2 = 0.03$, (other ps > .449).

Table 6
Means and Standard Errors (in parentheses) of Response Accuracy (%) and Reaction Times (ms).

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
ACC	73.40 (4.81)	72.02 (4.10)	74.86 (4.19)	68.89 (4.46)
RT	69185.24 (7187.20)	84466.47 (8219.07)	74891.92 (6644.19)	91529.00 (10248.62)

Note. ACC = Accuracy (percentage of correct responses), N = 116; RT = Reaction Time (in ms). N = 115.

Verbal Measures

Noise. A 2 (Choice) x 2 (Noise) ANOVA of the subjective noise ratings revealed a strong significant Noise main effect, $F(1, 112) = 167.50$, $p < .001$, $\eta^2 = .59$. Participants in the Noise condition (M = 75.89, SE = 2.67) rated the acoustic environment as significantly more unpleasant than those in the Silence condition (M = 25.56, SE = 2.86). Other effects were not significant ($ps \geq .15$). Moreover, in the Noise condition, the ratings were significantly higher than the scale's midpoint, $t(54) = 9.03$, $p < .001$, $\eta^2 = 0.60$. By contrast, in the Silence condition, they were significantly lower than the scale's midpoint, $t(60) = 9.14$, $p < .001$, $\eta^2 = 0.58$. This indicates that the noise stimulation was, as intended, perceived as unpleasant.

Difficulty. A 2 (Choice) x 2 (Noise) ANOVA of participants' difficulty ratings revealed a significant Noise main effect, $F(1, 112) = 4.06$, p =.046, $\eta^2 = .035$. Participants in the Noise condition (M = 41.21, SE = 2.90) rated the task as more difficult than those in the Silence condition (M = 32.11, SE = 3.32). Other effects were not significant ($ps \geq .08$). Besides the noise effect on difficulty, the difficulty ratings were significantly lower than the scale's midpoint according to one-sample *t*-tests, both for participants in the Noise condition ($M = 41.21$, $SE = 2.90$), $t(60) = 3.03$, $p = .004$, $\eta^2 = 0.13$, and participants in the Silence condition ($M = 32.11$, $SE = 3.32$), $t(54) = 5.39$, $p < .001$, $\eta^2 = 0.34$. This indicates that the perceived difficulty was low to moderate.

Interim Conclusions

Replicating Experiment 1, the main result of our second study was the significant predicted combined effect of the noise and choice of task characteristics manipulations on PEP reactivity during task performance—our most reliable measure of effort intensity. Participants in the Assigned Color condition showed again comparatively strong PEP responses when they were exposed to irrelevant noise during the moderately difficult memory task, while those in the Chosen Color condition were shielded against the noise effect, resulting in moderate PEP responses in both the noise and silence conditions.

In addition to the expected manipulation effect on PEP reactivity, in Experiment 2, the 3:1 *a priori* contrast pattern was also significant for the responses of HR and DBP. However, focused cell comparisons revealed that the predicted effort pattern was less pronounced than for PEP reactivity. This is, however, not surprising because PEP is the clearest indicator of beta-adrenergic sympathetic impact and thus the most sensitive effort index among these measures. In summary, the results of Experiment 2 replicated and extended the main finding of Experiment 1 and lend further support to our hypothesis that the personal choice of task characteristics can shield against noise effects on effort-related responses in the cardiovascular system.

PEP Reactivity: Statistical Integration of Study 1 and Study 2

The 3:1 *a priori* contrasts of cardiac PEP reactivity during task performance were significant in both studies. However, in Study 1, one of our independently conducted cell comparisons did not reach statistical significance: PEP reactivity in the Assigned Color/Noise condition was not significantly stronger than in the Chosen Color/Silence condition. In Study 2, PEP reactivity in the Assigned Color/Noise condition was not significantly stronger than in the Assigned Color/Silence condition. Therefore, we conducted an additional statistical analysis to combine the results of both studies and compared the relevant conditions that did not achieve statistical significance. To calculate cumulative *z*-scores, we used the adding *z* method (Rosenthal, 1978): We converted the one-tailed *p* level of each cell comparison to its associated *z*-score, then summed the *z*-scores, and finally divided the sum by the square root of the number of inference tests. The adding *z* method revealed the predicted cell differences, with significantly stronger PEP reactivity in the Assigned Color/Noise condition than in both the Assigned Color/Silence condition, $z = 3.14$, $p < .001$, and the Chosen Color/Silence condition, $z = 2.65$, $p = .004$.

General Discussion

In support of our conceptual hypothesis, the present two experiments found that personal choice of task characteristics leads to action shielding (Gendolla et al., 2021), and extends it to the yet unexplored context of irrelevant acoustic noise. Consistent with previous findings on irrelevant noise effects on physiological activation (e.g., Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Tafalla & Evans, 1997), participants in the present assigned task characteristics conditions showed stronger responses of cardiac PEP during task performance—our most sensitive measure of effort intensity (Kelsey, 2012; Wright, 1996; Richter et al., 2008)—when they were exposed to irrelevant noise than those who worked in silence. This compensatory effort allows individuals to cope with the distracting properties of noise on cognitive task performance, but may be linked to health risks: Cardiovascular reactivity has been identified as a key variable in the development of essential hypertension and cardiovascular disease (Baumann et al., 1973; Blascovich & Katkin, 1993; Krantz & Manuck, 1984; Light et al., 1992; Menkes et al., 1989; Steptoe & Ross, 1981; Treiber et al., 2003). When environmental factors (such as irrelevant noise) ask for compensatory effort and cannot be prevented, it is thus crucial to identify conditions that allow the maintenance of moderate cardiovascular activity. Therefore, the present study investigated noise effects on effort-related cardiovascular response under consideration of the moderating effect of personal choice.

Noise, Choice, and Effort

The main results of our two present studies were the replicated significant combined effects of the noise and choice of task characteristics manipulations on cardiac PEP reactivity during task performance. Participants in the assigned task characteristics conditions showed stronger PEP responses—the time interval between the onset of ventricular depolarization and the opening of the aortic valve—when they were exposed to irrelevant noise during task performance than those who worked in silence. We had expected this noise effect in the assigned task characteristics condition because our cognitive tasks were moderately difficult—as indicated by both the performance data and participants' verbal post performance difficulty ratings in both studies. In this moderately difficult task context, we expected the irrelevant noise to increase subjective demand during performance, resulting in subjectively high but feasible task demand and thus a strong sympathetically mediated response in participants' cardiovascular system, reflecting effort.

Importantly, when participants were asked to choose one of four colors in which the task stimuli would be presented, cardiac PEP reactivity was as expected moderately high and showed no evidence of a noise influence. Most relevant, compared to the Assigned Color/Noise condition, PEP reactivity in the Chosen Color/Noise condition was in both studies significantly attenuated, reflecting the expected shielding effect. We had predicted this finding because personal choice of tasks or task characteristics is known to lead to high commitment (Bandura, 2001; Bouzidi et al., 2022; Nenkov & Gollwitzer, 2012; Oettingen et al., 2001; Ryan & Deci, 2006), an action-oriented task-focus (Kuhl, 1986), and an implemental mindset (Gollwitzer, 1990). Consequently, personal choice should reduce the receptivity for potentially conflicting influences—people should become *shielded* against noise effects on effort.

In summary, we interpret our findings as indicating that personal choice can shield against noise effects on sympathetically mediated responses in the cardiovascular system that reflect effort. Our present experiments show that the way people engage in an action—by personal choice vs. external assignment—is decisive: Personal choice shields against irrelevant noise effects on effort. The present findings indicate shielding effects that go beyond previously studied affective stimulations where happy and sad mood have been experimentally induced by background music (Falk et al., 2022a, 2022b; Gendolla et al., 2021) or where participants were exposed to aversive conflict primes (Bouzidi & Gendolla, 2023a; see also Bouzidi & Gendolla, 2023b). Choice seems to immunize individuals against a variety of potentially conflicting influences, including distractive and unpleasant irrelevant noise.

Cardiovascular Effects

On the physiological level, we had focused on effects on PEP reactivity because it is the most sensitive measure of beta-adrenergic sympathetic impact on the heart and thus effort intensity (Kelsey, 2012; Richter et al., 2008; Wright, 1996). In Experiment 1, effects on SBP, DBP, and HR reactivity were not significant, although HR reactivity largely corresponded to the predicted effort pattern. In Experiment 2, the a priori contrast analysis also turned out significant for HR and DBP, although direct follow-up cell comparisons between the Assigned Color/Noise and Chosen Color/Noise conditions fell short of significance for DBP. Moreover, in the Chosen Characteristics condition the shielding effect on HR and DBP reactivity was less pronounced than for PEP. This is, however, not surprising, because PEP is the most reliable and valid measure of beta-adrenergic sympathetic impact among the cardiovascular activity indices we have assessed.

As a limitation, we acknowledge that in Experiment 1, the direct comparisons of PEP reactivity in the Assigned Color/Noise and Chosen Color/Silence conditions fell short of significance although the difference was in the expected direction. In Experiment 2, the stronger PEP reactivity in the Assigned Color/Noise condition than in the Assigned Color/Silence conditions only trended towards significance. However, most relevant, our combined analysis that compared the relevant cells achieved statistical significance, and the overall *a priori* contrast models were significant in both studies. Besides the significant overall contrasts, the most relevant effect occurred in the Noise condition. Here, PEP reactivity in both experiments was significantly weaker when participants could personally choose task characteristics than when those characteristics were externally assigned. That direct follow-up comparison demonstrates the predicted shielding effect against noise effects on effort. We report—to our knowledge for the first time—noise effects on cardiac PEP in assigned tasks. Previous studies found noise to influence cortisol and catecholamine excretion or self-reported effort (Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Tafalla & Evans, 1997).

Importantly, our present research focuses on the influence of beta-adrenergic sympathetic activity on the heart, as proposed by Wright's (1996) integration of motivational intensity theory (Brehm & Self, 1989) with Obrist's (1976, 1981) active coping approach. In compliance with the definition of effort as the mobilization of resources for action execution (Gendolla & Wright, 2009), our theory-based approach focused only on sympathetically mediated cardiovascular responses, and we refrained from explorative analyses of other parameters. It is, however, worth noting that other research domains propose that cardiac parasympathetic activity could also play a role in cognitive task processing (e.g., Grossman et al., 1990). Because our research is theorydriven and we do not see how effort, defined as the mobilization of resources for action execution (Gendolla & Wright, 2009), can be operationalized via parasympathetic influences, we leave these aspects to be investigated in distinct future studies.

Performance Effects

Regarding performance effects, which were not the primary focus of our studies, the exploratory analyses of participants' response accuracy found no consistent effects. Experiment 1 found a significant Choice x Noise interaction effect. *Post hoc* cell comparisons revealed that participants in the Chosen Color/Noise condition had a significantly higher percentage of correct responses than participants in the Chosen Color/Silence condition. Moreover, participants in the Chosen Color/Silence condition showed a significantly lower response accuracy than those in the Assigned Color/Silence condition. In Experiment 2, no significant performance effects were found. However, on the descriptive level, participants in the Assigned Color/Noise condition now tended to show the lowest response accuracy and speed. These findings suggest that the task to perform might play an important role regarding the presence and magnitude of noise effects on performance (see Banbury et al., 2001; Cohen & Weinstein, 1981; Smith, 1989 for reviews; Szalma & Hancock, 2011, for a meta-analytic synthesis). As supported by our two present studies, noise exposure does not necessarily cause deleterious effects on cognitive performance—possibly because of the mobilization of compensatory resources when the task or its characteristics are assigned (Evans & Johnson, 2000; Frankenhaeuser & Johansson, 1976; Lundberg & Frankenhaeuser, 1978; Hockey, 1997; Tafalla & Evans, 1997).

Effort-related responses in the cardiovascular system are of high relevance for occupational health. We thus focused on sympathetically mediated cardiovascular response rather than performance—performance is usually studied with longer tasks in within-person designs to account for large individual differences in response speed and accuracy. The link between effort and performance is more complex than simply linear. Effort intensity (behavioral input) and performance (behavioral output) are conceptually not identical and performance depends besides effort also, or even more, on persistence, task-related capacity, and applied strategies (Locke & Latham, 1990). The link between noise and performance is equally difficult to predict: A moderately difficult cognitive task paired with moderately intense acoustic noise—as used in our studies—should not necessarily affect task performance. If task difficulty is moderate, individuals should be able to cope with the distracting properties of noise through compensatory effort (see Smith, 1989, for an overview). Conclusive tests of the question whether personal choice can also immunize against noise effects on effort in highly difficult cognitive tasks will need to be conducted in the future.

Conclusion and Practical Implications

Our present studies show that the way people engage in an action—by choice vs. external assignment—is decisive: Personal choice can shield against irrelevant noise effects on sympatetically mediated cardiovascular responses during task performance. This could have practical implictations, as noise can adversely affect health, well-being, and performance (Szalma & Hancock, 2011). Acoustic noise at workplaces is manifold: It ranges from typical indoor office sounds such as telephone ringing, background speech, and air conditioning to sounds produced by construction work, and road, rail, or air traffic. By addressing the dynamic interrelationship between personal choice, irrelevant noise, and effort-related cardiovascular activation, our studies hold implications for the occupational health psychology literature, and practical suggestions for designing work conditions in which employees can continuously work productively while maintaining their health and well-being. These implications are of high relevance, because sources of irrelevant noise at workplaces are numerous, and noise exposure has been associated with compensatory effort when executing cognitive tasks. Compensatory effort might be associated with psychophysiological costs since cardiovascular reactivity has been identified as a key variable in the development of essential hypertension and cardiovascular disease (Baumann et al., 1973; Blascovich & Katkin, 1993; Krantz & Manuck, 1984; Light et al., 1992; Menkes et al., 1989; Steptoe & Ross, 1981; Treiber et al., 2003).

We identifiedight *personal choice* as a powerful psychological factor that shields action execution against irrelevant noise effects on cardiovascular responses. When engaging in action by personal choice of task characteristics, individuals working on an objectively moderately difficult tasks were protected from the irrelevant noise effect and maintained a moderate cardiovascular activation. This finding is of special importance in work settings where employees are exposed to frequent auditory disturbances that cannot be prevented. Although our study investigated university students rather than employees and administered standardized cognitive tasks rather than real work challenges, workers in various work settings must cope with cognitive demands with memory and attention aspects, which is highly similar to our laboratory task. We suspect the shielding effect of personal choice to operate across different environments, and hope that our findings encourage research to further investigate how and when giving employees personal choice of work aspects can protect them against detrimental noise effects. Our findings add to other already identified benefits of autonomy at the workplace (e.g., Bond & Bunce, 2001; Jackson, 1983). Consequently, fostering personal choice in noisy work environments may potentially contribute to protecting employees' cardiovascular health in the long run and might be considered when designing occupational noise mitigation strategies.

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Impact Statement

Noise Annoys—But Personal Choice Can Attenuate Noise Effects on Cardiac Response Reflecting Effort

Johanna R. Falk[1,2], Peter M. Gollwitzer[3], Gabriele Oettingen[3], and Guido H.E. Gendolla[1,2]

[1] FPSE, Section of Psychology, University of Geneva, Switzerland

[2] Swiss Center for Affective Sciences, University of Geneva, Geneva, Switzerland

[3] New York University, New York, USA

Acoustic noise during cognitive task performance can increase effort. Our two studies identify an important moderator of this effect: personal choice. In both studies, the opportunity to personally choose task characteristics shielded sympathetically mediated cardiovascular reactivity reflecting effort against noise influences during the performance of moderately difficult cognitive tasks. As predicted, sympathetically mediated cardiovascular reactivity was the strongest in tasks with externally assigned characteristics under noise exposure.

Supplementary Material

Noise Annoys—But Personal Choice Can Immunize against Noise Effects on Cardiac Response Reflecting Effort

Johanna R. Falk[1], Peter M. Gollwitzer[2], Gabriele Oettingen[2], and Guido H.E. Gendolla[1]

[1]University of Geneva, Switzerland

[2]New York University, USA

Experiment 1

General PEP Reactivity

Upon request of one reviewer, we tested if there was a general reactivity of PEP between the baseline assessment and task performance. The mean raw activity scores for PEP, HR, SBP, and DBP for the baseline and task performance periods appear in Supplementary Table S1. To test if task performance had a significant effect on cardiovascular activity, specifically our main dependent variable PEP, a repeated measures ANOVA was performed. Mean PEP activity differed significantly between the baseline vs. task performance periods, $F(1, 109) = 42.38$, $p < .001$, $\eta^2 = 0.28$. This effect was also highly significant when considering the Assigned Color/Noise condition only, in which we expected strongest PEP decreases, $F(1, 28) = 24.39$, $p < .001$, $\eta^2 = 0.47$.

Supplementary Table S1
Means and Standard Errors (in parentheses) of the Cardiovascular Values During Baseline Measures and Task Performance.

	Chosen Color		Assigned Color	
	Silence	Noise	Silence	Noise
PEP Baseline	97.18 (2.02)	98.55 (2.10)	97.33 (1.60)	96.79 (2.06)
PEP Task	95.27 (2.16)	97.38 (1.99)	96.54 (1.54)	93.76 (2.19)
SBP Baseline	100.67 (1.60)	103.31 (1.65)	102.64 (1.64)	103.29 (1.61)
SBP Task	106.41 (2.20)	107.67 (1.60)	106.99 (1.56)	107.42 (1.60)
DBP Baseline	57.71 (0.97)	57.55 (0.79)	58.08 (0.87)	58.29 (0.97)
DBP Task	61.01 (1.29)	60.94 (1.12)	62.96 (1.11)	61.74 (1.14)
HR Baseline	77.52 (2.24)	71.97 (1.39)	71.39 (1.76)	73.72 (1.82)
HR Task	81.54 (2.44)	75.44 (1.78)	74.07 (1.91)	78.05 (2.09)

Note. PEP = pre-ejection period (in ms), SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). $N = 112$ for SBP, DBP, HR; $N = 110$ for PEP.

CO and TPR Baseline Values

To provide a fuller picture of hemodynamic responses during task performance that were, however, not relevant for our hypotheses, we assessed and analyzed the responses of cardiac output (CO) and total peripheral resistance (TPR). CO was assessed with the ICG monitor and calculated by the Cardioscreen system according to the Sramek and Bernstein formula (see Bernstein, 1986). TPR was calculated from CO and mean arterial pressure (MAP = [2 x DBP + SBP] / 3) by using the formula TPR = (MAP / CO) * 80 (Sherwood et al., 1990). Given that we had no specific hypotheses about the responses of both hemodynamic indices, we first exploratively analyzed the cardiovascular responses with 2 (Choice) x 2 (Noise) ANOVAs.

Three outliers for the reactivity scores of TPR and two outliers for the reactivity scores of CO (> 3 *SDs* than the condition mean) were excluded from the analyses for the respective measures. We constituted CO and TPR baseline scores by averaging cardiovascular values of the last 3 minutes of the habituation period, which showed high internal consistency during the last three minutes (McDonald's ωs ≥ .989). Cell means and standard errors are displayed in Supplementary Table S2.

Supplementary Table S2
Means and Standard Errors (in Parentheses) of Baseline Values of Cardiac Output and Total Peripheral Resistance.

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
CO	5.91 (0.20)	6.10 (0.22)	5.59 (0.19)	5.95 (0.20)
TPR	996.05 (27.44)	964.28 (35.32)	1073.22 (44.41)	995.31 (31.11)

Note: CO = cardiac output (in liters per minute), TPR = total peripheral resistance (in dynes second per centimeter to the 5th power), *N* = 110 for CO, *N* = 109 for TPR.

Preliminary 2 (Choice) x 2 (Noise) ANOVAs of the cardiovascular baseline scores revealed no significant differences between the later conditions (*p*s > .120). Furthermore, we compared the baseline values of women and men with *t*-tests (including gender in the three-factorial ANOVA did not make sense because there were far more women than men in our sample). The gender analyses revealed a significant gender difference for TPR baseline values, $t(107) = 2.08$, $p = .04$, $\eta^2 = 0.04$. Women ($M = 1028.11$, $SE = 20.95$) had significantly higher baseline TPR values than men (*M* = 944.49, *SE* = 29.50). The CO gender analysis also showed a significant gender difference. Here, men had significantly higher baseline CO values (*M* = 6.35, *SE* = 0.19) than women (*M* = 5.72, *SE* = 0.11), $t(108) = 2.77$, $p = .007$, $\eta^2 = 0.07$.

CO and TPR Reactivity

We created reactivity scores by subtracting the baseline values from the averaged 1-min scores of CO and TPR assessed during the task. The 5 change scores for both measures showed high internal consistency (McDonald's ωs ≥.931) and were averaged. Cell means and standard errors appear in Supplementary Table S3.

Preliminary ANCOVAs found a significant association between baseline and reactivity scores of TPR, $F(1,109) = 10.59$, $p = .002$, $\eta^2 = 0.09$. Therefore, we analyzed baseline-adjusted reactivity scores of TPR to prevent possible carryover or initial values effect. There was no significant association between baseline and reactivity scores of CO ($p = .202$). Moreover, *t*-tests revealed no gender differences for CO or TPR reactivity scores (*p*s ≥ .735).

CO Reactivity. A 2 (Choice) × 2 (Noise) ANOVA of CO reactivity revealed neither significant main effects of Choice or Noise ($p \geq .407$), nor a significant Choice x Noise interaction effect ($p = .318$). The 3:1 a priori contrast that tested our predicted effort-related pattern was also not significant ($p = .192$)

TPR Reactivity. A 2 (Choice) × 2 (Noise) ANOVA of TPR reactivity found no significant Choice or Noise main effects (*p*s ≥ .777) and no significant Choice x Noise interaction effect (*p*s ≥ .674). The respective 3:1 contrast was also not significant ($p > .999$).

Supplementary Table S3
Means and Standard Errors (in Parentheses) of Cardiac Output and Total Peripheral Resistance Reactivity.

	Chosen Color		Assigned Color	
	Silence	Noise	Silence	Noise
CO	0.23 (0.05)	0.28 (0.14)	0.24 (0.05)	0.12 (0.08)
TPR	17.40 (11.30)	25.45 (20.06)	27.55 (13.89)	23.46 (11.31)

Note: CO = cardiac output (in liters per minute), TPR = total peripheral resistance (in dynes second per centimeter to the 5th power), *N* = 110 for CO, *N* = 109 for TPR.

Experiment 2

The calculation of cardiovascular indices and the data analysis were done as in Experiment 1. Again, three outliers for the reactivity scores of TPR and two outliers for the reactivity scores of CO (> 3 *SDs* than the condition mean) were excluded from the analyses for the respective measures.

General PEP Reactivity

The mean raw activity scores for PEP, HR, SBP, and DBP for the baseline and task performance periods appear in Supplementary Table S4.

Supplementary Table S4
Means and Standard Errors (in parentheses) of the Cardiovascular Values During Baseline Measures and Task Performance.

	Chosen Color		Assigned Color	
	Silence	Noise	Silence	Noise
PEP Baseline	96.85 (2.30)	98.70 (2.48)	98.00 (2.51)	100.39 (1.53)
PEP Task	95.05 (2.38)	96.39 (2.65)	95.38 (2.81)	96.15 (1.88)
SBP Baseline	103.70 (1.46)	103.08 (1.74)	101.04 (1.83)	103.59 (2.10)

SBP Task	107.69 (1.59)	109.40 (2.12)	105.23 (2.12)	109.87 (2.04)
DBP Baseline	57.87 (0.90)	57.99 (0.77)	57.38 (0.83)	58.30 (0.88)
DBP Task	60.39 (0.94)	62.33 (1.15)	60.27 (1.18)	63.99 (1.12)
HR Baseline	79.52 (1.87)	75.20 (1.92)	75.85 (2.41)	72.71 (1.86)
HR Task	83.10 (2.13)	82.72 (2.70)	81.18 (2.76)	80.40 (2.29)

Note. PEP = pre-ejection period (in ms), SBP = systolic blood pressure (in mmHg), DBP = diastolic blood pressure (in mmHg), and HR = heart rate (in beats/min). N = 115 for all measures except for DBP N = 116.

To test if task performance had a significant impact on cardiovascular activity, specifically our main dependent variable PEP, a repeated measures ANOVA correction was performed. Mean PEP activity differed statistically significantly between the baseline vs. task performance periods, $F(1, 114) = 59.62$, $p < .001$, $\eta^2 = 0.34$. This effect was also highly significant when considering only the Assigned Color/Noise condition, where we expected the strongest PEP decreases, $F(1, 30) = 23.55$, $p < .001$, $\eta^2 = 0.44$.

CO and TPR Baseline Values

The CO and TPR baseline scores showed again high internal consistency during the last three minutes of the habituation period (McDonald's ωs ≥ .993). Cell means and standard errors are displayed in Supplementary Table S5.

Supplementary Table S5
Means and Standard Errors (in Parentheses) of Baseline Values of Cardiac Output and Total Peripheral Resistance.

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
CO	5.94 (0.20)	5.74 (0.22)	6.15 (0.23)	5.44 (0.17)
TPR	1000.65 (31.02)	1053.50 (37.88)	959.10 (43.30)	1098.30 (39.16)

Note: CO = cardiac output (in liters per minute), TPR = total peripheral resistance (in dynes second per centimeter to the 5th power), *N* = 114 for CO, *N* = 113 for TPR.

Preliminary 2 (Choice) x 2 (Noise) ANOVAs of the CO baseline scores revealed a significant main effect of the later Noise condition, with higher values in the Silence condition (M = 6.04, SE = 0.15) than in the Noise condition (M = 5.58, SE = 0.14), $F(1,110) = 5.03$, $p = .027$, $\eta^2 = 0.04$. No other effects were significant (ps ≥ .211). Preliminary 2 (Choice) x 2 (Noise) ANOVAs of the TPR baseline scores revealed also a significant Noise main effect, this time with higher baseline values in the Silence condition (M = 1076.28, SE = 27.18) than in the Noise condition (M = 981.41, SE = 25.97), $F(1,109) = 6.41$, $p = .013$, $\eta^2 = 0.06$. Given that the noise manipulation was administered after the habituation period, we can only attribute those main effects to chance. No other effects were significant (ps ≥ .257).

Furthermore, we compared the baseline values of women and men with *t*-tests (including gender in the three-factorial ANOVA was again no option, because there were far more women than men in our sample). These analyses revealed no significant gender differences for the CO or TPR baseline values (ps > .542).

CO and TPR Reactivity

The 5 change scores for CO and TPR showed high internal consistency (McDonald's ωs ≥ .899) and were averaged. Cell means and standard errors appear in Supplementary Table S6. Preliminary ANCOVAs found no significant association between baseline and reactivity scores of CO or TPR ($p \geq .320$), suggesting that above reported Noise effect was not carried over to the task. Moreover, *t*-tests revealed no gender differences for CO or TPR reactivity scores (*p*s ≥ .301).

CO Reactivity. A 2 (Choice) × 2 (Noise) ANOVA of CO reactivity revealed a significant main effect of Choice with stronger responses in the Assigned Color condition ($M = 0.36$, $SE = 0.05$) than in the Chosen Color condition ($M = 0.18$, $SE = 0.04$), $F(1,110) = 7.33$, $p = .008$, $\eta^2 = 0.06$. The Noise main effect and the Choice x Noise interaction effect did not reach significance (*p*s ≥ .070). However, the 3:1 a priori contrast that tested our predicted effort-related pattern was significant ($p = .009$).

Additional focused one-tailed cell contrasts revealed that CO reactivity in the Assigned Color/Noise condition ($M = 4.12$, $SE = 0.8$) was significantly stronger than in the Chosen Color/Noise condition ($M = 0.24$, $SE = 0.6$), $t(110) = 1.94$, $p = .028$, $\eta^2 = 0.03$, and the Chosen Color/Silence condition ($M = 0.12$, $SE = 0.04$), $t(110) = 3.27$, $p < .001$, $\eta^2 = 0.09$. The difference between the Assigned Color/Noise and the Assigned Color/Silence ($M = 0.30$, $SE = 0.07$) conditions was in the expected direction but did not attain significance ($p = .104$).

while the cell contrast between the Chosen Color/Noise and Chosen Color/Silence conditions was significant, $t(110) = 2.25$, $p = .026$, $\eta^2 = 0.04$. However, in line with the predicted pattern, the differences between the Chosen Color/Noise and Assigned Color/Silence conditions and the Chosen Color/Silence and Assigned Color/Silence conditions were not significant (*p*s ≥

.155).

TPR reactivity. A 2 (Choice) × 2 (Noise) ANOVA of TPR reactivity revealed neither significant main effects of Choice or Noise (*p*s ≥ .265), nor a significant Choice x Noise interaction effect (*p*s ≥ .987). Also the 3:1 contrast was not significant (*p* = .797).

Supplementary Table S6
Means and Standard Errors (in Parentheses) of Cardiac Output and Total Peripheral Resistance Reactivity.

	Chosen Color		**Assigned Color**	
	Silence	**Noise**	**Silence**	**Noise**
CO	0.12 (0.04)	0.24 (0.06)	0.30 (0.07)	0.41 (0.08)
TPR	16.03 (8.04)	22.95 (11.73)	3.61 (6.16)	11.03 (14.15)

Note: CO = cardiac output (in liters per minute), TPR = total peripheral resistance (in dynes second per centimeter to the 5th power), *N* = 114 for CO, *N* = 113 for TPR.

Supplementary References

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