Singing Your Heart Out: Singing Pitch Accuracy Is Associated with Cardiovascular Responses of Task Engagement and Challenge/Threat During Vocal Performance

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The act of singing in evaluative contexts (e.g., singing in front of an audience) creates acute stress; however, individuals may vary in terms of the nature of stress responses. In the current work, we explored the relationship between singing pitch accuracy and individuals' cardiovascular stress responses during singing performance. In an initial vocal screening session, we assessed 60 university students' singing accuracy with a pitch imitation paradigm. Then, in a separate session, we examined the degree to which those who sang less accurately in the initial screening session—relative to those who sang more accurately—exhibited cardiovascular responses consistent with perceiving an active singing task to be manageable (challenge/threat responses), as well as important or valuable (task engagement). During both a singing and speech task, less accurate singers exhibited responses consistent with greater threat and lower task engagement, suggesting that they evaluated these tasks as less manageable and less important than did more accurate singers. Further, using hierarchical linear regression analyses, we found robust associations between singing pitch accuracy and challenge/threat responses in particular, existing above and beyond other theoretically relevant variables, including pitch discrimination, past singing training, and self-efficacy. Overall, the current results suggest valuable insight and directions for future research within the stress psychophysiology and singing cognition literatures.

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Key words: singing pitch accuracy, singing cognition, stress psychophysiology, challenge/threat, cardiovascular reactivity

Whether taking a difficult test or interviewing for a new job, everyday life is rife with acute stressors in the form of *motivated performance situations*, in which people must work to reach valued goals. Previous research conducted from the perspective of the biopsychosocial model of challenge/threat (BPSC/T; Blascovich, 2008; Blascovich & Tomaka, 1996; Seery, 2011, 2013; Seery & Quinton, 2016) and related frameworks (e.g., the theory of challenge and threat states in athletes, TCTSA; Jones et al., 2009; Meijen et al., 2020; Trotman et al., 2018) identifies reliable associations between individuals' performance quality and specific patterns of cardiovascular reactivity. Across a wide variety of cognitive and behavioral tasks, including golf putting, flight simulation, university coursework, and cricket batting, individuals who exhibit cardiovascular responses consistent with evaluating high resources/low demands (i.e., greater challenge) tend to perform better than those who exhibit responses consistent with evaluating low resources/high demands (i.e., greater threat; Blascovich et al., 2004; for reviews, see Behnke & Kaczmarek, 2018; Hase et al., 2018; Meijen et al., 2020).

Drawing from this research, we sought to explore the relationship between the accuracy of pitch matching during singing (henceforth "singing accuracy") and individuals' cardiovascular stress responses during performance. Vocal pitch matching ability, the most prominent feature in singing accuracy, is associated with large individual differences that are not yet fully understood (Wise, 2015). To date, research on pitch matching has focused primarily on cognitive and sensorimotor factors (e.g., Berkowska & Dalla Bella, 2009; Hutchins & Peretz, 2012; Loui, 2015; Pfordresher et al., 2015). However, singing can be a highly stress-inducing task, particularly for individuals who are conscious of their limited abilities. Therefore, stress-related, psychophysiological factors have a putative contribution to these individual differences in singing performance. As such, we sought to address the relationship between singing accuracy and cardiovascular challenge/threat responses.

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In a vocal screening session, we first assessed individuals' objective singing pitch accuracy with a pitch imitation paradigm. We then examined the degree to which singing pitch accuracy was associated with individuals' cardiovascular responses of challenge/threat (reflecting evaluations of ability to manage a singing task) as well as task engagement (reflecting evaluations of the importance or self-relevance of the singing task) in a secondary laboratory session. By non-invasively examining these responses during the act of singing, the current work broadens our understanding of singing as a novel and fruitful acute performance stressor, holding theoretical and practical implications for future psychophysiological research. In addition, we assessed challenge/threat responses in a simulated public speaking task to examine the specificity of the proposed association between singing pitch accuracy and cardiovascular responses. A major point of discussion in the music cognition literature concerns the degree of association between music and language (e.g., Patel, 2018). Evidence to date suggests that singing accuracy is associated with accuracy of matching speech intonation (Pfordresher & Mantell, 2014), and singing ability is associated with imitation of a foreign language (Christiner & Reiterer, 2013, 2015). We sought to address whether this apparent resource sharing across song and speech generalizes to the role of performance-based stress, with the prediction that the relationship between performance and stress responses may be specific to singing.

Stress responses in the present study were explored using the BPSC/T framework. The BPSC/T (Blascovich & Tomaka, 1996; Seery, 2011, 2013; Seery & Quinton, 2016) applies to motivated performance situations in which individuals carry out behaviors to reach self-relevant goals. Motivated performance situations result in the psychological state of *task engagement,* which represents the degree to which a goal is evaluated to be subjectively important or self-relevant. The goal in a motivated performance situation can be important or self-relevant for many reasons, both tangible (e.g., a monetary incentive) and intangible (e.g., effects on one's self-esteem). Task engagement is thought to activate the sympathetic-adrenomedullary axis, resulting in increases from baseline in both the rate at which the heart beats (heart rate, HR) and the force with which the heart's left ventricle contracts during each beat (ventricular contractility, VC; Seery 2011, 2013). Correspondingly, manipulations intended to heighten task engagement induces increases in these cardiovascular markers (e.g., Blascovich et al., 1999; Seery et al., 2009).

Task engagement is an important component of motivated performance situations, as it is a prerequisite for the psychological states of challenge/threat (Seery, 2011, 2013). *Challenge* occurs when individuals' evaluations of personal resources are relatively high, and their evaluations of task demands are relatively low. Conversely, *threat* occurs when individuals evaluate task demands as being relatively high and personal resources as being relatively low. Despite these discrete labels, challenge and threat represent two anchors of a single bipolar continuum, therefore relative differences in challenge/threat (i.e., greater vs. lesser challenge) are meaningful. Physiologically, whereas changes in HR and VC from baseline are used to index task engagement, challenge/threat is marked by the amount of blood pumped by the heart (cardiac output, CO) and a measure of net constriction versus dilation in the arterial system (total peripheral resistance, TPR). Challenge is thought to lead to greater release of epinephrine than threat, which yields relative dilation in arteries supplying skeletal muscles with blood (e.g., in the arms and legs), thereby facilitating the heart in pumping more blood (Seery 2011, 2013). A challenge response is associated with lower TPR and higher CO than threat, such that relatively lower TPR and higher CO reflect relatively greater challenge or lesser threat. The validity of these cardiovascular markers has been supported by dozens of studies investigating a range of topics (for reviews, see Blascovich, 2008; Seery, 2013), including the link between challenge/threat and performance quality (Hase et al., 2018; Kaczmarek et al., 2019; Meijen et al., 2020).

Although challenge/threat cardiovascular responses have largely been shown to be influenced by situation-specific factors in prior work (Blascovich, 2008; Seery, 2013), individuals may hold trait-like tendencies to exhibit greater challenge versus threat across situations, including greater propensities toward avoidance coping (Tomaka et al., 2018). Fitting this logic, individual differences in singing accuracy may be associated with challenge/threat responses that are more situation specific (i.e., resulting from individuals' psychological responses to the act of singing) or more general in nature (i.e., resulting from responses to both singing and speaking vocal performances). We hypothesized that less accurate (relative to more accurate) singing would be associated with cardiovascular responses consistent with greater relative threat during singing specifically but tested the alternative possibility as well.

Method

In the current study, participants completed an initial vocal screening session, which contained pitch imitation and pitch discrimination tasks. Participants who were easily able to distinguish differences in pitches separated by three semitones (i.e., 300 cents) or less were invited back to the second session in which the experimental tasks with concurrent physiological measures occurred. Participants with pitch thresholds greater than 300 cents were excluded because this was equal to starting pitch interval size in the adaptive test. Thus, participants with a resulting threshold of greater than 300 cents may have had trouble understanding directions, leading to a reversal of responses, or may have been exhibiting a pitch perception deficit more profound than most individuals classified with congenital amusia (e.g., Hyde & Peretz, 2004). We reasoned that participants fitting either category do not match the population of interest. Importantly, participants did not receive feedback regarding their performance on the pitch discrimination or imitation tasks prior to their second session. Instead, participants who met the screening criteria were simply invited to take part in an additional study session, which generally took place several days—or in some cases weeks—after their initial session in a separate experimental setting and location. Participants were not informed of whether the invitation to the second study session was contingent on their performance. They were simply provided instructions for how to sign up for the cardiovascular recording session, which was listed under a different study name and did not explicitly mention singing. The analyses we present below are based only on participants who were invited to the second session and successfully completed both study portions.[1] The study was approved by the University at Buffalo Institutional Review Board (Protocol # 030-821316). Informed consent was obtained verbally from all participants prior to each study session.[2]

PARTICIPANTS

Given that this work was the first to our knowledge to examine singing pitch accuracy in the context of cardiovascular responses of challenge/threat—as well as uncertainty surrounding the number of participants in our sample who would (a) meet the pitch discrimination criterion and (b) return for a secondary follow-up session—we sampled as many students in the initial study phase as personnel resources allowed. One hundred and thirty-four students from the University at Buffalo's Introductory Psychology pool participated in the screening procedure for course credit (*M* age = 19.63, *SD* = 2.34, 37% female). Forty-one of these participants (31%) were categorized as musicians based on the criteria of having five or more years of music training. Most of the participants reported English as their native language (*N* = 76, 57%). Chinese was the second most common native language reported (*N* = 33, 25%) and a variety of other native languages such as Arabic, Korean, and Spanish were also reported. In addition to allowing us to assess singing-related background items (e.g., past singing training), the procedure served as a vocal screening session to ascertain participants' pitch imitation abilities, determine that they did not exhibit profound pitch discrimination deficits, or did not possess hearing or vocal disorders (see details in Procedure below). As such, 83 participants (*M* age = 19.61 *SD* = 1.89, 32% female) were selected and agreed to participate in the cardiovascular recording session.

Of the 83 participants who were invited to the second session, 17 either cancelled or failed to attend their second experimental session, leaving 66 total participants who completed both portions of the study. In a typical challenge/threat study, approximately 10–15 percent of the sample may be lost due to cardiovascular recording problems. Of the 66 participants who completed both portions of the study, two participants were excluded from analyses due to unusable impedance cardiography data, and four participants were excluded due to technical issues during one of the two study sessions (e.g., computer froze, computer monitor fell from its mount during the session, signal interference in audio recordings during the vocal screening session). Further, three participants did not have blood pressure during the speech task, and an additional participant who did not have blood pressure data during the singing task. Since blood pressure readings are necessary to calculate standardized index scores of challenge/threat (but not task engagement), these participants were only included in analyses for task engagement responses. Thus, 60 participants were included in analyses for task engagement responses, while only 55 and 57 participants were

[1] We assessed singing pitch accuracy in a vocal screening session in order to maximize the quality of audio/recording data. However, in amenable acoustic environments, singing pitch accuracy can be collected and automatically processed by any device with an internet connection (for guidance on collecting singing pitch accuracy data online, see Pfordresher & Demorest, 2020)

[2] It was important for our hypotheses that participants were not aware that their invitation to the Cardiovascular Recording Session was contingent on their singing performance. For this reason, there was incomplete disclosure of the specific purposes and hypotheses of the study prior to the final debriefing session. Importantly, all required information for assessing participant risks and rights were provided at each stage of the study, including information about potential discomfort created by attachment of the physiological sensors and examples of possible performance stress tasks they could complete (e.g., puzzles, letter/number/image searches, math tasks, vocalizing aloud, interactions with others, answering questions). At this stage, participants were not told which specific performance stress tasks would be administered during their session.

included for challenge/threat responses in the singing and speech tasks, respectively. Using G*Power, we determined that the final sample sizes of 60 participants (task engagement responses), 55 participants (singing challenge/threat responses), and 57 participants (speech challenge/threat responses) used across analyses should have provided adequate power (>.80) to detect approximate effect sizes of η_p^2s = .135, .145, and .143, respectively.

APPARATUS

Participants' vocalizations during screening were recorded within a sound attenuated booth (Whisper Room Inc., SE 2000 Series, Morristown, TN). A Shure PG8 dynamic microphone connected through a Lexicon Omega preamplifier was used to digitally record these vocalizations at a sampling rate of 22,050 Hz. MATLAB served as the experimental interface for the presentation of auditory stimuli and vocal recordings. Sennheiser HD 280 Pro Headphones delivered sound at a comfortable intensity level based on lab standards and participant preferences.

CARDIOVASCULAR MEASURES

During the performance tasks, we used psychophysiological sensors to collect cardiovascular responses of task engagement and challenge/threat. As noted, task engagement is marked by changes in heart rate (HR) and ventricular contractility (VC) from baseline, whereas challenge/threat is marked by changes in cardiac output (CO) and total peripheral resistance (TPR). Our four cardiovascular markers were collected noninvasively, using accepted guidelines (Sherwood et al., 1990). We used the following equipment manufactured and/or distributed by Biopac Systems, Inc (Goleta, CA): NICO100C impedance cardiography (ICG) noninvasive cardiac output module, ECG100C electrocardiogram (ECG) amplifier, and NIBP100A/B noninvasive blood pressure module. ICG signals were detected with a tetrapolar aluminum/mylar tape electrode system, recording basal transthoracic impedance (Z0) and the first derivative of impedance change (dZ/dt), sampled at 1 kHz. Using a Standard Lead II electrode configuration (additional spot electrodes on the right arm and left leg, with ground provided by the ICG system), ECG signals were detected and sampled at 1 kHz. The blood pressure monitor was wrist-mounted, collecting continual readings (every 10–15 seconds) from the radial artery of participants' nondominant arm. Together, ICG and ECG recordings allowed computation of HR, VC (ms; i.e., preejection period reactivity $\times -1$), and CO (L/min). Blood pressure data were used to compute TPR (dyne-s/cm^5; mean arterial pressure $\times$ 80/CO; Sherwood et al., 1990). Recorded measurements of cardiovascular function were stored on a computer and analyzed offline with Biopac Acqknowledge 3.9.2 for Macintosh software, following techniques from previously published challenge/threat research (e.g., Seery et al., 2016), including ensemble averaging in 60s intervals (Kelsey & Guethlein, 1990). This approach is comparable to techniques used in other challenge/threat work with different equipment configurations (e.g., Jamieson et al., 2012; Turner et al., 2013; Vine et al., 2013). Scoring of cardiovascular data was performed blind to condition and other participant data.

VOCAL SCREENING SESSION PROCEDURES

Upon arrival, participants verified they had never been diagnosed with a hearing or voice disorder and then gave consent to participate. They were seated in the sound booth and engaged in three vocal warm-up exercises, including spontaneous vocal production (counting backwards from ten), the production of a single comfortable pitch, and production of the song *Happy Birthday to You* from memory. Participants then completed a pitch imitation task and a pitch discrimination task, with these tests counterbalanced across participants. The pitch imitation task consisted of eight trials in which participants heard and imitated four-note melodies. These melodies comprised the first five pitches from a major scale, selected from a set of scales based on optimal proximity to the participants' comfort pitch. The pitch discrimination task was a variant of the three-up, one-down adaptive pitch discrimination procedure used in Loui et al. (2008; for details, see Pfordresher & Demorest, 2020). In order to account for singing or musical history, participants in the vocal screening session were also asked to report their past music training (e.g., music lessons), as well as to describe the nature of this training.

CARDIOVASCULAR RECORDING SESSION PROCEDURES

Pre-task Questionnaires

Participants completed the subsequent cardiovascular recording session individually. This session began with the administration of brief preliminary questionnaires concerning performance stress in general. Specifically, participants completed the Interaction Anxiousness Scale (15 items, $\alpha = .88$; Leary & Kowalski, 1993), which focuses on individuals' feelings of anxiety in potentially evaluative situations (e.g., "I would be nervous if I was being interviewed for a job."), and the General Self-Efficacy Scale (8 items, $\alpha = .90$; Chen et al., 2001), which focuses on individuals' perceptions of being capable at completing tasks generally (e.g., "I will be able to successfully overcome many challenges").

Performance Tasks

Participants were then attached to the sensors and sat quietly for a 5-minute resting baseline period. All participants then heard recorded instructions explaining that the laboratory was interested in assessing physiological responses during various types of tasks and that they would be performing multiple tasks during their session. All participants then completed both a singing and speech task. The order in which participants completed the tasks was counterbalanced using random assignment, and the tasks were separated by an additional 5-minute rest period. Notably, specific instructions for singing and speaking tasks were only mentioned as part of the instructions that immediately preceded them. For instance, participants who completed the speech task first knew nothing of a singing task until after their speech was over.

For the singing task, participants heard recorded instructions explaining that they would be given one minute to sing *Happy Birthday to You* aloud twice (please see Supplementary Materials accompanying this paper at online.ucpress.edu/mp for complete set of lyrics). This duration was chosen to balance being long enough for reliable cardiovascular measurement while not so long to seem overly redundant to participants. Before beginning the 1-minute singing task, participants were given a 1-minute preparation period, during which they reviewed the song lyrics and imagined completing the task. Specifically, participants were asked to try to imagine themselves singing the words of the song and consider how they would feel while performing the task. This preparation period helped ensure that any differences observed in cardiovascular responses during the task were not simply due to differences in participants' abilities to spontaneously generate the song lyrics. Further, although our psychophysiological recording measures are best suited for active performance, it is theoretically possible that simply imagining one's experience during a stressor could induce proportional cardiovascular changes. Thus, by asking participants to imagine how they would feel during the stressor, this preparation period allowed us to better isolate the role of active performance specifically on shaping cardiovascular responses. Immediately following the preparation period, participants were told to begin singing and that they should attempt to sing for one full minute. If participants sang *Happy Birthday to You* twice before the 1-minute period ended, they were asked to continue singing until the experimenter told them that it was time to stop.

In order to examine the specificity of the relationship between singing pitch accuracy and cardiovascular responses, we also examined individuals' responses during a speech task. Speaking and singing share the same sensory, perceptual, and vocal-motor networks, therefore relying on common underlying processes (Zuk et al., 2022). Both tasks require similar bodily postures to facilitate respiration and phonation as well as incorporate the same articulators to produce a rich array of vocal sounds. Thus, we felt that the speech task served as a comparable control task in our investigation. For the speech task, participants were told that they would be giving a speech discussing their activities from yesterday. Participants were told they could discuss whatever they liked, including what they ate, places they went, things they saw, or what they did. Similar to the singing task, participants were provided a 1-minute preparation period, during which they were asked to imagine themselves delivering the speech and to consider how they would feel during the task. This preparation period was used to parallel participants' preparation period during the singing task. Following the preparation period, participants were told to begin their speech and were encouraged to speak for one minute. If participants stopped speaking for several seconds during this 1-minute period, the experimenter verbally prompted them to continue speaking until the time had elapsed.

Post-Task Questionnaires

After completing each task, participants responded to a series of items assessing their self-reported task evaluations, including the degree to which they exerted effort during each task (two items: *I tried hard during this task*; *I tried my best during this task*), were skilled or proficient at each task (three items: *I am not skilled at this task; I did well on this task; This task was difficult*), and enjoyed each task (three items; e.g., *I did not enjoy this task*; *I would enjoy doing this task again*; *This task is interesting*). All items were assessed on a 7-point scale ranging from 1 = *Completely disagree* to 7 = *Completely agree*.

After completing both tasks and responding to each task's self-report items, all participants completed a series of items assessing current affect (e.g., sad, shaky, afraid; 12 items) and demographic items, before being debriefed and thanked. For a full list of items and task instructions, please see Supplementary Materials accompanying this article at online.ucpress.edu/mp, as well as our Open Science Framework study profile (https://osf.io/tuw8g/?view_only=82d1707872ed413cb9a9364e0f5beee7).

DATA PREPARATION

Calculating Pitch Imitation from Vocal Screening Session Data

The accuracy of pitch imitation was based on measuring the vocal fundamental frequency (f_0) for each produced pitch, relative to the f_0 associated with the target pitch. First, f_0 values across the entire recording, both the target and the participant imitation, were extracted using the pitch-tracking algorithm YIN (de Cheveigné & Kawahara, 2002). Second, note boundaries were determined based on amplitude fluctuations associated with the stop consonant /d/ at the start of each sung note. Third, each note's pitch was estimated based on the median f_0 in the middle 50% portion of the note boundaries to control for the influence of extraneous pitch modulations (a.k.a., "scoops") common to the beginning and end of sung notes. Target pitches were computed in exactly the same way based on target recordings. Finally, absolute note deviations were generated by calculating the absolute difference between these pitch values and the target pitch for each note, and then averaged across all produced notes for a participant. Mean absolute pitch deviations varied considerably across participants in the final sample, from 17.19 to 333.81 ($M = 94.00$, $SD = 84.42$, skew = 2.43, kurtosis = 6.94). As in related work on singing pitch accuracy (Pfordersher & Larrouy-Maestri, 2015), absolute pitch deviations were log transformed and measured in cents.

Cardiovascular Measures

As is standard in challenge/threat research (e.g., Lupien et al., 2012; Saltsman et al., 2021; Scheepers et al., 2012), cardiovascular reactivity values were calculated by subtracting responses observed during the last baseline minute from those observed during the active task period for each type of task. For extreme reactivity values—using the a priori threshold of greater than 3.3 *SD*s from the mean ($p = .001$ in a normal distribution; Tabachnick & Fidell, 1996)—we winsorized values by adjusting each to be 1% above the next-highest non-extreme value (1 for CO in each task period; 2 for TPR in the singing task period; 1 for HR during the speech task period). Although this approach is not designed to achieve normality, it maintained the rank order in the distribution while decreasing the influence of a small number of extreme values.

Theoretically, changes in TPR and CO should reflect common underlying sympathetic-adrenomedullary activation, so that both indicate relative differences in challenge/threat. Thus, TPR and CO reactivity values were combined into a single index for singing period and, separately, the speech period (e.g., Blascovich et al., 2004; de Wit, et al., 2012; Seery et al., 2009). This served to: (a) maximize the reliability of the cardiovascular measures, analogous to averaging over multiple items on a self-report scale; and (b) assess the relative pattern across TPR and CO within participants (e.g., differentiating between individuals with high TPR and low CO vs. those with high TPR and moderate CO). We first converted participants' TPR and CO reactivity values ($r = -.65$, $p < .001$ for the singing task; $r = -.55$, $p < .001$ for the speech task) into *z*-scores and then summed reverse-scored TPR with CO (i.e., TPR was multiplied by –1 because TPR and CO should respond in opposite directions), such that lower values represented cardiovascular reactivity consistent with greater threat. The resulting index was then standardized for ease of interpretation ($M = 0$, $SD = 1$). Importantly, differences on this index are relative, such that the zero point represents the sample mean rather than a demarcation point between challenge versus threat. Similarly, HR and VC were also combined into a single index by summing their *z*-scores to examine differences in task engagement across conditions ($r = .61$, $p < .001$ for the singing task; $r = .36$, $p = .010$ for the speech task). The resulting index was standardized, with zero representing the sample mean rather than baseline levels. Results for individual measures are also reported. See Table 1 for a correlation matrix and descriptive statistics for all individual and composite measures.

Before assessing relative differences in challenge/threat or task engagement, we first confirmed that participants exhibited significant increases from baseline in HR and VC during both the singing and speech tasks. Testing these overall increases are central to testing challenge/threat analyses, as increases in HR and VC during task performance are prerequisites for both challenge and threat patterns. One-sample *t*-tests revealed that HR and VC reactivity were significantly greater than zero during the active singing period, HR (reported in beats per minute, bpm), $M = 6.19$, $t(59) = 7.03$, $p < .001$; VC (reported in ms; represents pre-ejection period multiplied by -1), $M = 3.72$, $t(59) = 3.61$, $p < .001$; and the active speech period, HR $M = 8.11$, $t(59) = 9.80$, $p < .001$; VC $M = 2.28$, $t(59) = 2.59$, $p = .010$. Establishing this evidence for task engagement justified testing for relative differences in both task engagement and challenge/threat responses.

Results

KEY ANALYSES

Using Stata 16.0 statistical software, we tested our hypothesized effects using regression analyses, with

TABLE 1. *Correlations and Descriptive Statistics*

Measure	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.	22.
1. Singing Pitch Accuracy	-																					
<u>Singing Task Period</u> (CV)																						
2. CT Index	−.36**	-																				
3. CO Reactivity	.34*	.91***	-																			
4. TPR Reactivity	−.31*	.91***	.64***	-																		
5. ENG Index	−.23†	.31*	.35**	−.22	-																	
6. HR Reactivity	−.22†	.24	.25†	−.19	.90***	-																
7. VC Reactivity	−.20	.33*	.39*	−.20	.90***	.61***	-															
<u>Speech Task Period</u> (CV)																						
8. CT Index	−.32*	.73***	.68***	−.64***	.24†	.10	.33**	-														
9. CO Reactivity	.32*	.59***	.72***	−.35**	.22†	.05	.34**	.88***	-													
10. TPR Reactivity	−.23†	−.68***	−.48***	.76***	−.19	−.11	−.23†	−.88***	−.53***	-												
11. ENG Index	−.26*	.14	.20	−.05	.73***	.61***	.69***	.17	.24†	−.06	-											
12. HR Reactivity	−.28*	.10	.08	−.10	.55***	.63***	.35**	.00	.03	.03	.83***	-										
13. VC Reactivity	−.15	.13	.24†	.01	.65***	.37**	.79***	.28*	.37**	−.12	.83***	.36**	-									
<u>Exploratory Variables</u>																						
14. Task Order	.17	.22	.22	−.19	.21	.25†	.13	.05	.00	−.07	−.05	−.05	−.03	-								
15. Singing Training (SR)	−.06	−.06	.03	.14	.15	.11	.17	−.05	.01	.09	−.07	−.14	.04	−.07	-							
16. Pitch Discrimination	.33*	−11	−.18	.02	−.24†	−.24†	−.19	−.05	−.08	.00	−.29*	−.24	−.24†	.06	−.18	-						
17. ENG Index CV: Preparation	−.22†	.19	.24†	−.10	.76***	.66***	.71***	.21	−.15	−.15	.73***	.59***	.62***	.15	.01	−.27*	-					
18. CT Index CV: Preparation	−.14	.67***	.63***	−.59***	.27*	.22	.28*	.51***	−.46***	−.46***	.09	.01	.13	.19	.04	−.04	.21	-				
19. General Self-Efficacy (SR)	.26*	−.09	−.16	.01	−.22†	−.24†	−.15	.03	−.12	−.12	−.27*	−.31*	−.13	−.05	.01	−.06	−.22†	−.17	-			
20. Interaction Anxiousness (SR)	−.08	.14	.14	−.11	.09	.07	.10	.02	.00	.00	.25†	.26*	.16	.27*	−.24†	−.14	.14	−.17	.00	-		
21. Post-Task Evaluations (SR)	−.26*	.13	.15	−.08	.14	.23†	.02	.09	−.08	−.08	−.13	−.02	−.19	−.22	.26†	.06	.03	.01	−.15	−.39**	-	
22. State Affect (SR)	.03	−.05	−.03	.06	.13	.11	.12	−.12	.14	.14	.31*	.28*	.24†	.36**	−.05	−.16	.04	−.14	−.25	.55***	−.43***	-
M	4.26	0	−0.11	148.51	0	6.19	3.72	0	−0.17	144.06	0	8.11	2.28	1.48	0.20	3.52	0	0	5.08	2.98	4.58	1.94
SD	0.77	1	1.60	268.80	1	6.82	7.98	1	1.52	183.83	1	6.41	6.83	0.50	0.40	1.37	1	1	0.80	0.69	0.70	0.45

Note. CV = Cardiovascular; SR = Self-report; CT index = challenge/threat. CO = cardiac output. TPR = total peripheral resistance. ENG index = task engagement. HR = heart rate. VC = ventricular contractility (preejection period reactivity × −1). † $p < .10$. * $p < .05$. ** $p < .01$. *** $p < .001$.

a continuous measure of singing pitch accuracy (log transformed absolute pitch deviations measured in cents; see Pfordresher & Larrouy-Maestri, 2015, for justification) as our predictor variable and standardized index scores of challenge/threat and task engagement as our outcome variables. We examined all cardiovascular measures during active portions of the singing and speech tasks, as our physiological markers are best interpreted in the context of active motivated performance situations. Given that we expected singing pitch accuracy to be theoretically unrelated to responses during non-singing tasks, we report analyses separately for the singing task and speech task. We report partial eta squared (η_p^2) as a measure of effect size for each result. As described in Steiger (2004), 90% confidence intervals (CIs) rather than 95% CIs reflect $\alpha = .05$ for η_p^2 and correspond to p values, given that η_p^2 cannot be negative.

Challenge/Threat

During the act of singing, we predicted that those who sang less accurately, relative to those who sang more accurately, should evaluate holding relatively low resources to meet the demands associated with a singing task, reflected in exhibiting greater relative threat. Consistent with hypotheses, singers who were less accurate exhibited cardiovascular responses consistent with greater relative threat during the singing task compared to singers who were more accurate, CT-index, $b = -0.39$, $t(52) = -3.24$, $p = .002$, $\eta_p^2 = .17$, 90% CI [.04, .31]. Unexpectedly, relatively inaccurate singers also exhibited greater relative threat during the speech task, CT-index, $b = -0.32$, $t(54) = -2.55$, $p = .014$, $\eta_p^2 = .11$, 90% CI [.01, .25].[3] Thus, the relationship between singing pitch accuracy and challenge/threat responses was consistent across the two tasks.

Task Engagement

Although it seemed plausible that all individuals could view singing as generally self-relevant and important, a perceived lack of singing pitch accuracy could instead lead less accurate singers to disengage from singing. Consistent with this possibility, we found that less accurate singers, relative to more accurate singers, exhibited cardiovascular responses consistent with *lower* task engagement during the singing task, ENG-index, $b = -0.28$, $t(57) = -2.19$, $p = .033$, $\eta_p^2 = .08$, 90% CI [.00, .20]. Interestingly, paralleling our challenge/threat responses, the same pattern of responses emerged during the speech task as well, with less accurate singers exhibiting lower task engagement than did those who sang relatively accurately, ENG-index, $b = -0.26$, $t(57) = -2.02$, $p = .048$, $\eta_p^2 = .07$, 90% CI [.00, .19].[4] Thus, compared to relatively accurate singers, relatively inaccurate singers exhibited less task engagement during both the singing and speech tasks.[5]

HIERARCHICAL REGRESSION MODELS

Given the correlational nature of these data, we examined the degree to which the relationship between singing pitch accuracy and cardiovascular responses existed above and beyond other notable theoretical variables. Specifically, we conducted hierarchical regression analyses to assess whether additional covariates of interest could account for the observed relationships between singing pitch accuracy during the vocal screening session and the physiological responses during the cardiovascular recording session. Given that the association between singing pitch accuracy and challenge/threat responses demonstrated nearly identical patterns and interpretations across the active singing and speech tasks, we combined cardiovascular response data across the active task periods, resulting in two hierarchical linear regression models (one for challenge/threat responses across tasks; one for task engagement responses across tasks).

In both models, we sequentially introduced covariates into the statistical model in 6 steps. In Step 1, we introduced the continuous measure of singing pitch

[3] In addition to challenge/threat index scores, we also report the analyses for CO and TPR separately. Singing task: CO, $b = -0.61$, $t(52) = -3.08$, $p = .003$, $\eta_p^2 = .154$, 90% CI = [.033, .298]; TPR $b = 90.94$, $t(52) = 2.67$, $p = .010$, $\eta_p^2 = .121$, 90% CI [.017, .260]). Speech task: CO, $b = -0.49$, $t(54) = -2.51$, $p = .015$, $\eta_p^2 = .104$, 90% CI [.012, .246]; TPR, $b = 45.78$, $t(54) = 1.90$, $p = .063$, $\eta_p^2 = .063$, 90% CI [0, .190].

[4] In addition to task engagement index scores, we also report the analyses for HR and VC separately. Singing task: HR, $b = -1.80$, $t(57) = -2.11$, $p = .040$, $\eta_p^2 = .072$, 90% CI [.001, .195]; VC, $b = -1.84$, $t(57) = -1.78$, $p = .080$, $\eta_p^2 = .053$, 90% CI [0, .180]. Speech task: HR, $b = -1.81$, $t(57) = -2.19$, $p = .032$, $\eta_p^2 = .078$, 90% CI [.003, .202]; VC, $b = -1.016$, $t(57) = -1.12$, $p = .268$, $\eta_p^2 = .022$, 90% CI [0, .115].

[5] Despite showing similar associations, it was plausible that the nature and relative magnitude of the relationship between singing pitch accuracy and cardiovascular responses diverged between the two tasks. In order to test the degree to which cardiovascular response differences were specific to the singing task (vs. the speech task), we conducted a series of mixed-effects model analyses examining the interaction between task type (i.e., singing vs. speech; within-subjects variable) and singing pitch accuracy (between-subjects variable) on cardiovascular responses of challenge/threat and task engagement. Both with and without including task order as a covariate in the statistical models, we found no evidence that task type moderated the relationship between singing pitch accuracy and challenge/threat cardiovascular reactivity, $Fs < 1.91$, $ps > .148$, or the relationship between singing pitch accuracy and task engagement cardiovascular reactivity, $Fs < .68$, $ps > .509$.

accuracy. In Step 2, we introduced task order to ensure that responses did not vary as a function of which task participants performed first. We then introduced singing-specific factors, including singing training (Step 3) and pitch discrimination skills (Step 4), which assesses individuals' ability to accurately hear and discriminate between different pitches (rather than vocally reproduce them). In order to assess whether response differences were specific to active performance (vs. anticipation of performance), we then introduced individuals' cardiovascular responses during the preparation period into the statistical model (Step 5).[6] Finally, in Step 6, we introduced the suite of self-report measures, which included trait-like measures assessed at the beginning of the cardiovascular recording session (General Self-Efficacy and Interaction Anxiousness), and state measures of task evaluations and affect assessed after task performance. To simplify the hierarchical model and reduce the risk of multicollinearity (Kraha et al., 2012), we created composite measures for task evaluations and affect. Specifically, because all eight task evaluation items were significantly correlated across singing and speech tasks ($r = .60$, $p < .001$), we combined all items into a single post-task evaluation index ($\alpha = .82$), with higher scores reflecting more positive evaluations of the tasks. Similarly, we combined all state affect items into a single state affect index ($\alpha = .73$), with higher scores reflecting more positive affect/less negative affect.

Challenge/Threat Responses

Consistent with our primary analyses, singing pitch accuracy was associated with greater relative threat across the singing and speech tasks in Step 1 of the analyses, $\beta = -.37$, $p = .006$. Predictably, challenge/threat responses in the preparation period were also significantly associated with challenge/threat responses in the active performance period, $\beta = .57$, $p < .001$ (Step 5). Upon introduction of each new variable (including the preparation challenge/threat responses), the relationship between singing pitch accuracy and challenge/threat responses remained significant, including in the full model with all covariates, $\beta = -.30$, $p = .017$, indicating that this relationship existed above and beyond all other variables in the model (see Table 2 for full model; see Supplementary Material accompanying this paper at online.ucpress.edu/mp for hierarchical steps).

TABLE 2. ***Full Model With All Covariates: Challenge/Threat Outcome Variable***

Variable	b	SE b	β	p	η_p^2
Singing Pitch Accuracy	−0.30	0.12	−.30	.017	.12
Task Order	0.11	0.24	.06	.646	.01
Singing Training (SR)	−0.16	0.27	−.06	.567	.01
Pitch Discrimination	0.08	0.12	.08	.497	.01
Task Engagement (CV; Preparation)	0.03	0.11	.03	.766	.00
Challenge/threat (CV; Preparation)	0.63	0.11	.63	< .001	.42
General Self-Efficacy (SR)	0.16	0.12	.17	.183	.04
Interaction Anxiousness (SR)	0.21	0.14	.19	.135	.05
Post-task Evaluations (SR)	0.14	0.14	.13	.323	.02
State Affect (SR)	−0.01	0.16	−.01	.929	.00
Full Model R^2					.56

Note: CV = Cardiovascular Measure; SR = Self-report Measure

Task Engagement Responses

We further investigated the relationship between singing pitch accuracy and task engagement responses. Although remaining significant (or marginally significant) in Steps 1, 2, and 3 of the analyses (i.e., when past singing training was introduced), βs > −.26, *p*s < .052, the relationship between singing pitch accuracy and task engagement responses became nonsignificant when introducing pitch discrimination into the model (Step 4), $\beta = -.22$, $p = .123$. Overall, task engagement responses in the preparation period were significantly associated with task engagement responses in the active performance period, $\beta = .76$, $p < .001$ (full model). The relationship between singing pitch accuracy and task engagement responses remained nonsignificant in the full model with all covariates, $\beta = -.06$, $p = .509$ (see Table 3 for full model; see Supplementary Material accompanying this paper at online.ucpress.edu/mp for hierarchical steps).

TESTING A NEW MODEL OF SINGING PITCH ACCURACY

Past correlational studies have shown that perceptual (Pfordresher & Nolan, 2019) and sensorimotor (Greenspon & Pfordresher, 2019) functions account for less than 30% of variance in singing pitch accuracy, leaving over 70% of variance unaccounted for. Thus, we tested one final hierarchical linear regression model to examine the degree to which our variables of interest,

[6] Although participants were not actively performing during the anticipation period, we did observe indication of task engagement, warranting the investigation of challenge/threat differences. Specifically, one-sample *t*-tests revealed that HR and VC reactivity were significantly greater than zero during the preparatory singing period, HR $M = 2.90$, $t(59) = 3.79$, $p < .001$; VC $M = 2.51$, $t(59) = 2.93$, $p = .004$; and the preparatory speech period, HR $M = 3.20$, $t(59) = 5.11$, $p < .001$; VC $M = 2.21$, $t(59) = 3.43$, $p = .001$.

TABLE 3. *Full Model With All Covariates: Task Engagement Outcome Variable*

Variable	b	SE b	β	p	η_p^2
Singing Pitch Accuracy	−0.06	0.10	−.06	.509	.01
Task Order	−0.16	0.19	−.08	.420	.02
Singing Training (SR)	0.12	0.22	.05	.585	.01
Pitch Discrimination	−0.01	0.10	−.01	.932	.00
Task Engagement (CV; Preparation)	0.76	0.10	.76	<.001	.61
Challenge/threat (CV; Preparation)	0.10	0.10	.09	.308	.02
General Self-Efficacy (SR)	0.01	0.10	.01	.887	.01
Interaction Anxiousness (SR)	0.00	0.11	.00	.981	.00
Post-Task Evaluations (SR)	0.09	0.11	.08	.411	.02
State Affect (SR)	0.30	0.12	.29	.016	.12
Full Model R^2					.71

Note: CV = Cardiovascular Measure; SR = Self-report Measure

TABLE 4. *Full Model: Singing Pitch Accuracy Outcome Variable*

Variable	b	SE b	β	p	η_p^2
Challenge/Threat (CV; Performance)	−0.41	0.17	−.40	.021	.12
Task Engagement (CV; Performance)	−0.04	0.22	−.04	.855	.00
Task Order	0.37	0.28	.18	.199	.04
Singing Training (SR)	0.11	0.33	.04	.742	.00
Pitch Discrimination	0.33	0.14	.32	.020	.12
Task Engagement (CV; Preparation)	0.05	0.21	.05	.835	.00
Challenge/threat (CV; Preparation)	0.12	0.17	.12	.493	.01
General Self-Efficacy (SR)	0.24	0.14	.24	.089	.07
Interaction Anxiousness (SR)	−0.10	0.17	−.09	.571	.01
Post-Task Evaluations (SR)	−0.23	0.16	−.21	.172	.04
State Affect (SR)	−0.02	0.20	−.01	.936	.00
Full Model R^2					.41

Note: CV = Cardiovascular Measure; SR = Self-report Measure

including all cardiovascular, self-report, and singing-specific measures, individually and cumulatively accounted for observed variance in singing pitch accuracy during the vocal screening session. Treating continuous singing pitch accuracy as the outcome variable, we sequentially introduced our variables of interest into the model. In Step 1, we introduced cardiovascular responses of challenge/threat and task engagement during active performance. The remaining steps were parallel to the models above: introducing task order (Step 2), singing training (Step 3), pitch discrimination (Step 4), preparation period cardiovascular responses (Step 5), and self-report measures (Step 6).

Overall, the full statistical model accounted for approximately 41% of variance in singing pitch accuracy, which is more variance than prior investigations capturing sensorimotor and perceptual processes of singing alone (see Table 4). Of core interest in the current research, challenge/threat responses during performance uniquely accounted for a substantial proportion of total variance observed in singing pitch accuracy, $\eta_p^2 = .062$. This relationship between challenge/threat and singing pitch accuracy existed above and beyond all other variables in the model, $\beta = -.40$, $p = .021$, including pitch discrimination, which was also significantly related to singing pitch accuracy, $\beta = -.32$, $p = .020$. Notably, in the full model, task engagement responses were not significantly associated with singing pitch accuracy, $\beta = -.04$, $p = .855$, suggesting that challenge/threat responses during performance—but not task engagement responses—may be more fundamental to accounting for variance in singing pitch accuracy.

Discussion

OVERVIEW OF FINDINGS

Applying the perspective of the BPSC/T, we hypothesized that individual differences in singing pitch accuracy would be related to specific patterns of cardiovascular stress responses during the act of singing. Supporting our hypothesis, we found that less accurate singers exhibited cardiovascular responses consistent with greater relative threat (lower CO, higher TPR) while singing. This, in turn, is consistent with an explanation that poor singing accuracy is associated with evaluating low resources and high demands while singing.

Unexpectedly, less accurate singers also exhibited cardiovascular responses consistent with greater relative threat while *speaking* about a neutral topic (i.e., participants' activities from the day before). Thus, individuals' singing pitch accuracy, an objective measure of performance quality, appears to not only be related to cardiovascular responses during active singing performance, but also a non-singing task as well. Overall, this suggests that differences in singing pitch accuracy may be related to broader motivational tendencies that exist outside of the scope of singing performance and coheres with findings suggesting the use of shared resources during song and speech production (cf. Mantell & Pfordrsher, 2013; Patel, 2018; Zuk et al., 2022).

We held competing hypotheses regarding the relation between individual differences in singing accuracy and cardiovascular responses reflecting task engagement, or perceived importance of performance. Although it seemed plausible that all individuals could view singing as generally self-relevant and important (high task engagement), a perceived lack of singing pitch accuracy could instead lead less accurate singers to disengage from singing (low task engagement). Overall, we found evidence for the latter possibility, such that singing less accurately, compared to singing more accurately, was associated with lower task engagement. Interestingly, and parallel to our challenge/threat findings, task engagement responses were not unique to the act of singing, emerging during the speech task as well. Again, these findings suggest that singing pitch accuracy may be associated with broader motivational tendencies during active performance stressors.

Using a series of hierarchical linear regression models, we further assessed the robustness of the relationships between singing pitch accuracy and cardiovascular responses of challenge/threat and task engagement during active performance, assessing these effects alongside other relevant constructs in our study. Although findings for task engagement were somewhat tenuous, singing pitch accuracy accounted for a significant proportion of variance in challenge/threat responses, existing above and beyond several potentially pertinent factors, including pitch discrimination skills, general self-efficacy, past singing training, and even cardiovascular responses during a preparation period.

KEY CONTRIBUTIONS AND IMPLICATIONS

The current results contribute to the understanding of mechanisms underlying individual differences in singing accuracy. Much of the existent literature in singing cognition focuses on perceptual (Pfordresher & Nolan, 2019) and sensorimotor (Greenspon & Pfordresher, 2019) explanations for deficits in singing pitch accuracy. These factors account for a relatively small portion of total variance in singing accuracy, roughly 30% across individuals. In our model, challenge/threat responses across singing and speech tasks accounted for a significant proportion of observed variance in singing pitch accuracy that may contribute in addition to these more cognitive factors. When challenge/threat is combined with singing-specific factors (e.g., pitch discrimination skills, singing training), as well as other potentially related psychological factors (e.g., general self-efficacy), our overarching model accounted for over 40% of variance in singing pitch accuracy. We believe these findings emphasize the utility of cross-disciplinary collaborative research.

Further, the current study provides a potentially valuable methodological contribution to the psychophysiology of stress. Beyond the BPSC/T and TCTSA, there is interesting potential for the use of singing in stress psychophysiological research broadly, as singing tasks potentially hold multiple key advantages over other commonly used paradigms (e.g., Le et al., 2021). First, many paradigms in the stress psychophysiology literature, such as public speaking, lack the experimental control that singing predetermined lyrics provide. Second, speaking and singing provides a source of comparison that is more easily controlled and potentially more direct (e.g., comparisons between singing a song versus reciting the lyrics), than comparisons often used in the literature (e.g., contrasting the Trier Social Stress Test versus watching films, e.g., Hawn et al., 2015; Mochizuki et al., 2019). Third, the large individual differences in singing performance provides a rich source of individual variability to explore.

Finally, our work contributes to research examining cardiovascular responses and performance quality in two notable ways. One, the vast majority of research in the BPSC/T literature focuses narrowly on challenge/threat reactivity as a measure of interest. Discussion of task engagement outcomes is often limited to simple *t*-tests to indicate whether performers are engaged overall. Recently, more research has focused on exploring the role of task engagement specifically in shaping performance outcomes; however, contradictory findings have emerged. On the one hand, the threat-provoked motivational disengagement hypothesis argues that greater threat may create the conditions for disengagement, and thus, performance deficits (Hase et al., 2020; Richter et al., 2008). On the other hand, research also finds evidence that threat could potentially foster greater engagement, demonstrating that potentially threatening situations (e.g., poor initial performance at a video game task) can actually predict greater cardiac activity in a subsequent task (Behnke et al., 2021). Taken together, the current work not only expands upon newly emerging work examining the antecedents of singing accuracy, but provides novel contributions to the field of psychophysiology as well.

LIMITATIONS

In the current study, we predicted that less accurate singers, relative to more accurate singers, would exhibit greater threat during the act of performance, reflecting an evaluated lack of resources to meet the demands of singing in the moment. However, in the current work, we found evidence that singing pitch accuracy was not only related to greater threat in a singing task, but in a non-singing speech task as well. We believe this finding may indicate that singing pitch accuracy is related to broad motivational tendencies, a possibility that is also grounded firmly in the BPSC/T and TCTSA. Specifically, although varying across situation-specific factors, challenge/threat may also be indicative of general trait-like motivational tendencies (e.g., propensity toward avoidance coping tendencies; Moore et al., 2019; Tomaka et al., 2018).

Related to this point, although the current investigation identifies an association between singing pitch accuracy and cardiovascular responses, the underlying mechanism(s) and causal direction of this association remain unclear. Drawing from existing challenge/threat literature, resource/demand states and manipulations have reliably predicted both physical and cognitive performance outcomes via a wide range of mechanisms, including emotional and motor/kinematic processes (Behnke et al., 2022; Moore et al., 2012), as well as cognitive appraisals and motivations (Trotman et al., 2018). We suspect the same should be true for singing, wherein challenge/threat states could impact basic emotional, cognitive, motivational, and motor/kinematic processes involved in the act of singing, thereby impacting performance. Over time, this association may become circular, with challenge/threat responses hindering objective singing quality, which then further affects challenge/threat responses to singing. Future research could explore the causal direction of these variables in various ways. For instance, participants could be provided false feedback about their singing performance before screening for singing pitch accuracy. Alternatively, to examine changes in response to motivated performance, singing pitch accuracy could be assessed both before and after an evaluative singing task.

Finally, we assessed responses across two different tasks; however, the current work is still limited in its scope to vocal performance tasks. Speaking and singing share psychological mechanisms and overlapping neural networks (Peretz et al., 2015; Zuk et al., 2022), therefore presumably relying on common underlying processes. Individuals with superior pitch imitation abilities likely possess refined development of the vocal-motor system and these auxiliary mechanisms. For this reason, individuals with a high degree of vocal competency may evaluate a vocally related task as being more manageable, which would result in greater relative challenge across tasks. Although this possibility still provides a novel contribution to the existing literature, it does limit the generalizability of our findings to the context of vocal-specific tasks, and not to active performance stressors more broadly. Future work should examine participants' responses across a wider range of motivated performance situations, including those that do not require vocal production specifically.

A FINAL NOTE

Life is a performance, and thus, full of performance stressors. From job interviews to public speaking opportunities, people routinely brush up against acute stress in the form of motivated performance situations, in which they must actively engage in behaviors to meet important goals. The act of singing, particularly in evaluative contexts (e.g., singing in front of an audience, a camera, or an experimenter), has been validated as a potent source of acute stress, increasing various markers of sympathetic nervous system arousal (e.g., heart rate, systolic blood pressure; Le at al., 2021). Although the act of singing may invoke a generalized autonomic stress response, the precise nature of this response should vary across individuals, with some individuals comfortably and confidently rising to the lofty demands of this stressor, and others feeling incapable of meeting such demands.

In the current work, we predicted that less accurate singers, relative to more accurate singers, may fall into this latter category, exhibiting cardiovascular responses consistent with evaluating low resources/high demands (i.e., greater threat) in the moment of singing. During both active singing and speech tasks, we found that less accurate singers, relative to more accurate singers, not only exhibited cardiovascular responses consistent with greater threat, but responses consistent with placing less value and importance on their performance (i.e., less task engagement). Although the relationship between singing pitch accuracy and task engagement was found to be less reliable, hierarchical regression analyses revealed a robust association between singing pitch accuracy and challenge/threat responses, existing above and beyond other theoretically relevant variables, including pitch discrimination, past singing training, and self-efficacy. Building on previous work examining the antecedents of singing pitch accuracy, we not only found that challenge/threat responses accounted for among the highest proportion of variance in our investigation, but our overall statistical model accounted for over 40% of variance in singing pitch accuracy. This marks a significant advancement over past theoretical models, which focused primarily on sensorimotor and perceptual functions and accounted for less than 30% of variance in singing pitch accuracy. Taken together, we believe the current results provide valuable insight and directions for future research within the stress psychophysiology literature. Moreover, our findings provide practical and theoretical advancements in the singing cognition literature, potentially uncovering some unsung explanations for why some singers are inaccurate in the first place, and why they may remain so over time.

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