A meta-analysis

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ABSTRACT

Cardiovascular responses to challenge and threat have been used extensively in psychophysiological research. In this meta-analysis, we scrutinized the body of evidence for the role of challenge and threat hemodynamic responses in predicting positive behavioral outcomes, i.e., performance quality. We accounted for cardiac output (CO), total peripheral resistance (TPR), and Challenge-Threat Index (CTI). With 17 articles covering 19 studies (total N = 1045), we observed that the literature might have been biased towards positive results. After we excluded outlying studies and compensated for missing null-effect studies, we found that the mean standardized coefficient, corrected with the trim-and-fill method, was r = 0.14 for CO, r = −0.13 for TPR, and r = 0.10 for CTI. This indicated relatively small but stable effects of cardiovascular responses in the facilitation of successful performance. Moderator analyses indicated that TPR and CTI produced stronger effects in non-experimental studies. We also found that effects were not moderated by levels of engagement (indexed by heart rate and pre-ejection period), task domain (cognitive vs. behavioral) and measurement method. In summary, our results supported the general validity of the biopsychosocial model in the prediction of behavioral outcomes. However, they also indicated limitations of the empirical evidence and a significant bias in the literature.

1. Introduction

The challenge and threat paradigm has become one of the leading theoretical frameworks for physiological responses during a motivated performance (Blascovich et al., 2004; Seery et al., 2009; Turner et al., 2012). Challenge and threat studies capitalize on cardiovascular (CV) biosignals that provide continuous and relatively unobtrusive access to the correlates of action-oriented cognitive processes (Seery, 2013). The challenge and threat cardiovascular response has been studied to identify inhibiting and facilitating factors in several diverse contexts of daily life such as coping with stereotype threat among minority members and women (Mendes et al., 2008), training skills, e.g., laparoscopic surgery (Vine et al., 2013), practicing sports, e.g., climbing (Turner et al., 2014), taking exams (Seery et al., 2010), or negotiating (Scheepers et al., 2012).

The concept of healthy and unhealthy responses to demanding tasks, such a challenge vs. threat cognitive appraisal (Lazarus and Folkman, 1984) or eustress vs. distress (Selye, 1976), has been discussed in the literature for decades. However, there has been a more recent and ongoing debate within the literature regarding the physiological specificity of these cognitive processes (Wright and Kirby, 2003). For instance, theorists have argued for specific CV (Blascovich, 2008), hormonal (Jamieson et al., 2010), and behavioral (Jones et al., 2009) responses to challenge and threat appraisals as well as their role in the facilitation of goal-oriented actions. Some authors have claimed that CV markers of challenge and threat are superior in comparison to self-reported evaluations because an accurate report of inner states and experiences is likely to be problematic to some individuals and is not feasible for some research designs (Seery et al., 2010, Nisbett and Wilson, 1977). The validity of CV markers of challenge and threat has also been supported experimentally because individuals with stronger challenge-type CV responses are more successful at goal attainment (Gildea et al., 2007; Moore et al., 2012).

Building upon these works, we have used a metanalytical approach to test the overall strength and consistency of relationships between challenge and threat physiological markers and successful performance across different life domains. Scrutinizing the body of empirical evidence for the biopsychosocial model is worthwhile because it summarizes what studies have been conducted and evaluates their strengths and limitations, e.g., the diversity of tested populations, research designs, or methods of measurement. Meta-analyses are robust tests for theories that inform meaningful decision in further studies, e.g., which populations or types of activity are understudied or what effects sizes could be expected while determining the sample size. Finally, a meta-

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analysis is likely to provide an empirical test for the integrity of the literature, revealing or discounting the occurrence of any publication-bias.

1.1. Physiological responses to challenge and threat

Challenge and threat appraisals occur when individuals are motivated to engage in active goal pursuits and do their best, e.g., while taking school exams (Seery et al., 2010), negotiating prices (Scheepers et al., 2012), or learning new skills (Moore et al., 2014). Cognitive evaluations of the self and the environment feed the motivational system that mobilizes the physiological resources that are necessary for action (Mendes and Park, 2014). Increased goal-oriented motivation leads to increased sympathetic activation in the autonomous nervous system, which results in increased heart rate (HR) and shortened pre-ejection period (PEP) (Seery, 2011). Thus, individuals with stronger motivational intensity display higher HR and PEP reactivity. This initial physiological response is further modulated after individuals evaluate personal action resources (e.g., skills, knowledge, and abilities) and situational demands (e.g., solutions that need to be found using cognitive skills or motor actions that require considerable dexterity).

Challenge motivation occurs when individuals identify the sufficiency of resources to overcome demands. Adrenaline is released into the bloodstream, which results in widening of blood vessels (vasodilation) and this then produces lower total peripheral resistance (TPR) (Brownley et al., 2000). It also results in higher cardiac output (CO) (i.e., the amount of blood pumped by the heart). In contrast, when demands exceed personal resources, individuals perceive the situation as threatening. Threat appraisal inhibits the release of adrenaline and instead releases cortisol. In these circumstances, the arteries narrow, despite the increased HR. This results in higher TPR with relatively lower CO. This CV pattern has been related to challenge and threat using several manipulations. For instance, challenge and threat was introduced by changing the presence of an audience (Feinberg and Aiello, 2010), changing the gain and loss probability (Seery et al., 2009), or using downward and upward social comparison opportunities (Mendes et al., 2001).

The following four indexes of CV reactivity have been used within the challenge and threat paradigm: HR, PEP (i.e., time in the cardiac cycle from initiation of ventricular depolarization to the opening of the aortic valve and ejection of blood into the vasculature), CO (i.e., the amount of blood pumped by the heart per minute), and TPR (i.e., net constriction vs dilatation in the arterial system). TPR has been typically calculated by dividing mean arterial pressure by CO and then multiplying the total by 80 (Sherwood et al., 1990). Several authors have used the Challenge-Threat Index (CTI), which integrates the TPR and CO information, based on the assumption that the TPR and CO are two related measures of the same underlying nervous system activation (Blascovich et al., 2004). For instance, CTI can be used in regression analysis by converting TPR and CO values into z-scores and summing them, with an assigned weight of −1 for TPR and 1 for CO. The theoretical framework for these CV responses was built upon Dienstbier’s (1989) model of psychophysiological toughness, which has since been validated (see Blascovich, 2008; Seery, 2011 for reviews).

1.2. Challenge, threat, and performance

The challenge-type CV response is more efficient at energy mobilization than the threat-type because it provides greater blood flow to the periphery (Seery, 2011). Previous research has shown that individuals who endorse a challenge-type motivation are more likely to achieve a superior performance in cognitive tasks (Gildea et al., 2007; Mendes et al., 2008; Turner et al., 2012), and motoric activities (Blascovich et al., 2004; Moore et al., 2012; Moore et al., 2013; Turner et al., 2013). Furthermore, challenge and threat CV markers predict academic success (e.g., Seery et al., 2010). These findings indicate that challenge and threat CV responses predict a broad range of behavioral outcomes.

1.3. Present study

The present study aims to test whether or not CV responses to threat and challenge are related to a successful performance. While studies have reported significant effects (Turner et al., 2012) and some have reported null-effects (Moore et al., 2012), it was imperative to employ a meta-analytical approach that tests the robustness of the available findings. Furthermore, we examined the potential moderators that might explain the heterogeneity of the findings across different studies; that is, the domain of performance (cognitive vs. motor activity) and the CV markers of motivation intensity in participants to complete the task (HR and PEP reactivity). The metanalytical approach provides statistical tools that inform whether a publication bias (e.g., refraining from the publication of null findings) was likely to occur for this particular body of research (Duval and Tweedie, 2000). It is essential to account for this type of bias because the problem of poor replicability of findings in psychology has been observed (Francis, 2012). Publication bias has been indicated to be one of the main reasons for this problem.

2. Method

2.1. Search strategy

We performed a systematic literature search in PsychInfo, PubMed, and Google Scholar covering the period from 1993 (first attempt of using of challenge and threat CV markers) (Tomaka et al., 1993) to January 2017. We used the following terms: “challenge” or/and “threat” in combination with one of the other expressions: “performance,” “cardiovascular,” “CO,” “TPR,” “CTI” (for details, see Fig. 1). We also cross-checked the references in the studies that we retrieved and contacted 25 authors that had published papers on the question of challenge and threat. We asked these authors for any unpublished material. The search was restricted to peer-reviewed studies in English. A total of 20 authors responded to the request but they did not report any unpublished research results.

2.2. Selection of studies

We selected potentially eligible studies in two phases. First, we scrutinized the titles and abstracts. If the material was relevant to the subject of this meta-analysis, we then screened the full-text articles. All of the studies that were identified as potentially eligible during the first selection phase were then re-assessed in the second selection phase. The inclusion criteria were as follows: the study was developed within the challenge and threat paradigm; the performance was quantified; relevant CV markers were provided; available data of each study required for the calculation of effect sizes. If necessary, the authors were contacted for supplementary data. A total of 12 authors sent re-analyzed results with the requested coefficients.

2.3. Study coding

The first author coded all of the studies that met the inclusion criteria. The studies were then coded for the inclusion of CV reactivity measures, performed task, type of performance (cognitive vs. behavioral), type of measurement, research design (experimental manipulation vs no manipulation), number of participants, and age.

2.4. Data selection and extraction

This meta-analysis aimed to assess the effect of CV markers of challenge and threat on successful performance. Thus, we only considered those performances that had objective and quantifiable
outcomes. Relevant data for every measure included in the analysis were extracted and entered into an Excel spreadsheet. Our search and e-mail requests yielded 38 potentially relevant articles. After examining these articles and discarding any irrelevant studies (e.g., missing objective performance outcomes), we identified 17 articles that met all of the inclusion criteria (for details, see Fig. 1). These studies included 19 independent samples, with 27 effect sizes and the total sample size of 1045 participants. A list of studies and the additional characteristics of the meta-analysis are presented in Table 1.

2.5. Meta-analysis strategy

For the meta-analysis, we used the correlation between the CV markers and the performance outcomes as a measure of the effect size. For most studies, the authors reported correlation coefficients. For studies reporting other metrics (e.g., group-level comparisons, challenge vs. threat), we sent a request to the authors to re-analyze the data and provide relevant results. To calculate the pooled mean effect sizes, we used R (R Core Team, 2017) with packages metafor (Viechtbauer,
tematically suppressed from publication in the challenge and threat analysis to investigate whether null or weak results have been significantly likely to be missing in the meta-analysis because of the performance, Measurement method = method used to obtain physiological measures, type = performance type, UUS = paper characterized participants as un-study dispersion due to real di-

dicates low, 50% moderate, and 75%, high heterogeneity (Higgins 2000; Schmidt and Hunter, 2014). We tested for the presence of het-

terests model because the diversity of the outcomes in these studies was evidenced by the 95% con-

Table 1

Studies examining the effects of challenge and threat CV markers on successful performance.

| ID   | Authors            | N  | CO  | TPR | CTI | HR(d) | PEP(d) | Age | Measurement method | Performance task | Type | Research design |
|------|--------------------|----|-----|-----|-----|-------|--------|-----|--------------------|------------------|------|-----------------|
| 1    | Blascovich et al., 2004 | 27 | 0.40 | −0.40 | 0.46 | 3.61  | 1.93   | UUS | ICG, ECG, CBP     | Baseball         | 0    | 0               |
| 2    | Chalabaev et al., 2009 | 27 | 0.53 | −0.36 | 1.84 | 1.57   | UUS   | ICG, ECG, CBP | Problem-solving | 1    | 1               |
| 3    | Ell et al., 2011a  | 17 | 0.33 | −0.22 | 0.46 | −0.46  | 22.7  | ICG, ECG, CBP | Rule-based categorization| 0    | 1               |
| 4    | Ell et al., 2011b  | 16 | −0.67 | 0.71 | −0.46 | 22.7  | ICG, ECG, CBP | Information-integration | 0    | 1               |
| 5    | Frings et al., 2015 | 48 | −   | −   | −0.05 | 0.45  | 21.75 | ICG, ECG, CBP | Word finding | 1    | 0               |
| 6    | Mendes et al., 2008 | 110| 0.26 | −0.21 | 1.54 | UUS   | ICG, ECG, CBP | Word finding | 1    | 1               |
| 7    | Moore et al., 2012 | 122| −0.05 | 0.03 | −0.26 | 274  | 19.5  | ICG, ECG, BP     | Golf putting     | 0    | 1               |
| 8    | Moore et al., 2014 | 115| 0.13 | −0.09 | 0.08 | 2.45   | 21.5  | ICG, ECG, BP | Laparoscopic surgery | 0    | 1               |
| 9    | Moore et al., 2015 | 42 | 0.22 | −0.17 | 0.24 | 2.16   | 20.2  | ICG, ECG, BP     | Golf putting     | 0    | 1               |
| 10   | Moore et al., 2013 | 59 | 0.04 | −0.2  | 0.12 | 2.09   | 22.9  | ICG, ECG, BP | Golf putting     | 0    | 1               |
| 11   | Scheepers, 2009    | 40 | −0.04 | 0.01 | 0.03 | 1.42   | UUS   | ICG, ECG, CBP | Word finding | 1    | 1               |
| 12   | Scheepers et al., 2012 | 65 | −0.05 | 0.01 | 0.05 | 0.69   | 20    | ICG, ECG, CBP | Negotiation      | 1    | 1               |
| 13   | Scholl et al., 2017 | 49 | 0.27 | −0.35 | 0.41 | 0.71   | 1.43  | 22    | ICG, ECG, CBP | Number bisection | 1    | 0               |
| 14   | Seery et al., 2009 | 72 | 0.21 | −0.12 | 0.17 | 2.45   | 1.78  | UUS   | ICG, ECG, CBP | Remote associations | 1    | 1               |
| 15   | Seery et al., 2010 | 95 | 0.25 | −0.22 | 0.25 | 3.15   | 1.59  | UUS   | ICG, ECG, CBP | SAT             | 1    | 0               |
| 16   | Turner et al., 2012a | 25 | 0.35 | −0.45 | 0.4  | 0.9    | 2.12  | 34    | ICG, ECG, CBP | Stroop test      | 1    | 0               |
| 17   | Turner et al., 2012b | 21 | 0.33 | −0.36 | 0.37 | 1.91   | 1.68  | 21.1  | ICG, ECG, CBP | Netball shooting | 0    | 0               |
| 18   | Turner et al., 2013 | 42 | 0.52 | −0.51 | 0.65 | 1.27   | 1.23  | 16.5  | ICG, ECG, CBP | Cricket batting | 0    | 0               |
| 19   | Vine et al., 2013   | 52 | 0.18 | −0.18 | 0.285 | 3.235  | 18.7  | ICG, ECG, CBP | Laparoscopic surgery | 0    | 0               |

Note: Id = study identification number, N = number of participants, CO = cardiac output, TPR = total peripheral resistance, CTI = Challenge-Threat Index, HR (d) = effect size for increases in heart rate between baseline and performance, PEP(d) = effect size for increases in pre-ejection period between baseline and performance, Measurement method = method used to obtain physiological measures, type = performance type, UUS = paper characterized participants as undergraduate university students, ICG = impedance cardiography, ECG = electrocardiography CBP = continuous blood pressure, BP = blood pressure. Performance type coded 0 = behavioral, 1 = cognitive; Research design coded as 0 = non-experimental, 1 = experimental.

2010) and robustmeta (Fisher and Tipton, 2015) following meta-analysis recommendations (Quintana, 2015). We decided to use the random effects model because the diversity of the outcomes in these studies was high and considerable heterogeneity was likely. Several theorists have advocated for the adoption of random effects models for meta-analysis as these models are optimal in permitting the generalization of corrected effect sizes to the population (Field, 2001; Hunter and Schmidt, 2000; Schmidt and Hunter, 2014). We tested for the presence of heterogeneity based on two parameters. First, we calculated the Q statistic. A significant Q rejects the null-hypothesis of homogeneity and indicates that the true effect size probably does vary from study-to-study. Second, the F-statistic was calculated. This is a percentage indicating the study-to-study dispersion due to real differences over and above the random sampling error. A value of 0% indicates an absence of dispersion and larger values show increasing levels of heterogeneity, where 25% indicates low, 50% moderate, and 75%, high heterogeneity (Higgins et al., 2003).

In line with recommendations, we performed a publication-bias analysis to investigate whether null or weak results have been systematically suppressed from publication in the challenge and threat literature (Schmidt and Hunter, 2014). We checked whether any effect sizes were likely to be missing in the meta-analysis because of the publication bias. This type of analysis is vital because studies with non-significant or negative results are less likely to be published in peer-reviewed journals (Borenstein et al., 2009). We inspected a funnel plot depicting the relationship between standard error and effect size, and then ran a trim-and-fill analysis (Duval and Tweedie, 2000).

Finally, we performed moderator analyses by testing the differences in mean correlation coefficients between subgroups. A moderator was considered effective if the average corrected effect sizes calculated in each moderator group were significantly different from each other, as evidenced by the 95% confidence intervals. Moderation was further supported if the moderator resulted in a narrowing of the credibility intervals and an increase in the variance accounted for by statistical artefacts. To report the results, we applied Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009).

Based the biopsychosocial model (Blascovich, 2008; Seery, 2013), we expected that several factors might be explored as potential moderators: a type of performance (behavioral vs. cognitive), measurement method (continuous vs. discrete measurement of blood pressure), research design (experimental manipulation vs. no manipulation), and metabolic engagement level (indexed by the reactivity measures of HR and PEP or ventricular contractility (VC)). Some studies term PEP as ventricular contractility multiplying PEP by −1 (e.g., Mendes et al., 2008). For these studies, we calculated PEP by multiplying changes in VC by −1. Examples of the type of performance included behavioral (e.g., netball shooting, laparoscopic surgery) and cognitive (e.g., modified Stroop Test performance, remote associations test (RAT)) tasks. As for the measurement methods, all studies included electrocardiography (ECG) and impedance cardiography (ICG) measures. Blood pressure was measured beat-by-beat in 14 studies, and discrete measurements were taken in five studies. Nine studies (47%) used an experimental design to influence the challenge and threat appraisal. The remaining studies measured undisturbed challenge and threat levels preceding the performance. We found no substantial diversity of studies in the sample to test differences between sports vs non-sports behavioral activity, precision movements (e.g., darts) vs gross body movements (e.g., running). This resulted from the fact that the majority of studies (n = 6, 75%) involved sports that required gross body movements, whereas only one behavioral activity used in two studies (n = 2, 25%) was non-sports (surgical skills). In contrast, the sample of studies with cognitive tasks was highly heterogenic and measured diverse cognitive skills such as attention (n = 4, 36%), reasoning (n = 3, 27%), categorization (n = 2, 18%), communication (n = 1, 9%), problem solving (n = 1, 9%). Thus, there were few studies to test differences between each cognitive category.
3. Results

3.1. Effect sizes

Table 1 presents the summary statistics for the studies included in the analysis. This table also provides the coding that we used to conduct the moderator analyses. Fig. 2 shows that nearly all correlations between performance outcomes and CTI, and CO were positive, and for TPR were negative. CV markers with higher reactivity levels were associated with higher levels of performance.

The analysis produced a “bare bones” correlation coefficient representing the mean average effect size corrected for the sampling error. The random effects model showed that the average Performance correlation was $r = 0.21$, 95% CI [0.10, 0.32], $p < .01$, for CTI, $r = 0.19$, 95% CI [0.08, 0.30], $p < .01$, for CO, and $r = -0.17$, 95%CI [−0.26, −0.08], $p < .01$, for TPR.

The test for heterogeneity revealed significant levels for CTI $Q_{(14)} = 35.10$, $p < .01$, CO $Q_{(17)} = 42.96$, $p < .01$, and TPR $Q_{(17)} = 36.78$, $p < .01$. This rejected the null-hypothesis of homogeneity and it indicated that the true effect size was likely to vary from study-to-study. Moreover, the variability in effect sizes indicated by the $I^2$ statistic suggested that there were differences in the population between studies for CTI ($I^2 = 61.42$), CO ($I^2 = 60.68$), and TPR ($I^2 = 47.08$). We investigated the source of this heterogeneity through a Bajaut plot analysis, which identifies studies that contribute to the overall heterogeneity and the overall results. Two studies were identified as problematic (Turner et al., 2013; Ell et al., 2011). Removing these outlying results reduced effect sizes for all three CV markers: $r = 0.17$, 95% CI [0.08, 0.26], $p < .01$, for CTI, $r = 0.17$, 95% CI [0.09, 0.26], $p < .01$, for CO, and $r = -0.16$, 95% CI [−0.24, −0.09], $p < .01$ for TPR. It also reduced the heterogeneity substantially to a non-significant level of $Q$ statistics CTI $Q_{(13)} = 20.54$, $p = .08$, CO $Q_{(14)} = 21.10$, $p = .10$, and TPR $Q_{(14)} = 16.14$, $p = .31$. The remaining heterogeneity was moderate or small for CTI ($I^2 = 36.31$), CO ($I^2 = 32.44$), and TPR ($I^2 = 14.30$).

3.2. Publication bias analyses

We found indications of publication bias for all of the CV markers. Egger’s regression test was statistically significant for CTI ($t = 2.46$, $p < .01$), CO ($t = 1.96$, $p < .05$), and TPR ($t = -2.47$, $p < .01$). Therefore, we recalculated the mean effect sizes with missing studies filled using the Trim-and-Fill method (see Fig. 3). We imputed the effects of four missing studies for CTI, and the effect size was reduced to $r = 0.10$, 5% CI [0.01−0.21]. Three studies were imputed for CO, and the adjusted effect size was $r = 0.14$, 95% CI [0.05−0.22]. Four studies were imputed for TPR, and the recalculated effect size was $r = -0.13$, 95% CI [−0.20, −0.06].

3.3. Moderator analyses

The type of performance (behavioral vs. cognitive), the metabolic engagement level and measurement method did not moderate the relationship between CTI, CO, TPR and the level of performance (Table 2). Therefore, the researcher decision on applying the manipulation to change individuals motivational states (yes/no) was a significant moderator for TPR $Q_{(1)} = 4.53$, $p = .03$, and CTI $Q_{(1)} = 9.04$, $p < .01$, but not for the CO $Q_{(1)} = 1.89$, $p = .17$. The relationship was significantly higher for non-experimental studies ($r = -0.25$ for TPR, $r = 0.24$ for CTI) compared to experiments ($r = -0.09$ for TPR, $r = 0.03$ for CTI).

4. Discussion

Individuals who maintain challenge motivation are more likely to achieve critical life outcomes (see Blascovich, 2008, for a review). One of the hypothesized reasons why challenge evaluations are beneficial pertains to favorable physiological responses to challenge (e.g., increased adrenaline secretion that provides high cardiac efficiency) and negative responses to threat (e.g., impeded blood flow to tissues and decreased venous flow back to the heart). In the current study, we performed analyses that tested whether the effects of CV markers on successful performance that are reported in the literature are robust and unbiased. We observed that some studies that supported the challenge and threat hypothesis had shown exaggerated effects compared to other studies. Furthermore, we found statistical evidence that studies reporting weaker effects are under-represented in the literature. However, even when controlling for these biases, the association between the level of performance and CV markers of challenge and threat was significant. This is an argument for the validity of the biopsychosocial model in the prediction of performance (Blascovich, 2008; Seery, 2013). Yet, the effects that we observed were small, with most of the variance in performance unexplained. This finding is a caveat for the model and its practical utility.
meaningful behavioral differences that are likely to accumulate over time (psychological significance). This questions if the relationship between CV responses and performance might be modeled in a way that explains more variance. However, it is also likely that results from the use of non-invasive methods of CV measurement are suppressed by their limited capacity to reflect the actual hemodynamic processes (Dyson et al., 2010; Shibasaki et al., 2010).

Of the CV indexes, CTI displayed the lowest effect size. CTI performed relatively poorer, by 30–40%, when compared to the raw indexes of CO and TPR. This is an argument against its utility in the context of performance. This difference might result from the derivative nature of this index; that is, CTI results from transformations such as standardizing two different variables and adding them along with their measurement error. Another problem with the CTI is that it seems to have no direct physiological parallel in any specific physiological process. Alongside our empirical arguments, these conceptual arguments might suggest that measures such as CO and TPR that are directly related to specific physiological processes offer a higher predictive accuracy.

We found that for studies with an experimental manipulation the relationship between TPR and CTI (but not CO) and performance was smaller than for non-experimental studies. This suggests meaningful differences between these two research designs. These moderating effects might result from the interference of manipulation with naturally occurring appraisals and physiological responses. Yet, other differences between the experimental and non-experimental studies that were not accounted for might be responsible for these moderating effects.

The moderator analysis indicated that the association of CO and TPR with the level of performance did not depend on the level of engagement. HR and PEP did not moderate this relation significantly. In line with the biopsychosocial model, increases in HR and PEP from the baseline are common across the challenge and threat continuum, whereas they are associated with higher task engagement observed in larger changes (Seery, 2011). This supports the assumption of the BPS model that challenge and threat do not differ across the level of engagement. We also noticed no differences across task domains and measurements methods. For physical and cognitive tasks, the relationship between CO, TPR, and successful performance was similar. These findings suggest that the model can be applied to different contexts of life.

We found two kinds of evidence that the literature regarding challenge and threat and performance is somewhat biased towards the positive. First, we observed that some studies reported effects that were above statistical expectations. This suggests that the distribution of effects for the CV markers might be bimodal with most effects within a low effects range and some within a higher range. Researchers might address this hypothesis in further studies that might replicate these outlying findings (Turner et al., 2013; Ell et al., 2011). Second, we found that some studies (16–28%) might be missing. If they do indeed exist, then these papers would report null results or results that were against the theory-based hypotheses. This publication gap might result from authors who decided not to publish all of their findings or they may stem from the decisions of reviewers and journal editors who might be more likely to decide against publication of such findings, or they may be a combination of both (Franco et al., 2014; Rosenthal, 1979). It is, therefore, imperative for the integrity of the psychophysiological science that both processes are minimized.

This study has several limitations. First, with our focus on psychophysiology, we accounted for the physiological markers of challenge and threat rather than the self-report of challenge and threat. Further studies might try to extend these findings and test the robustness of the association between cognitive evaluations, physiological responses, and behavioral outcomes. However, this is a problematic aim for a meta-analysis given a high diversity of methods to measure self-reported challenge and threat which increases homogeneity between indicators (Field and Gillett, 2010). The preferred strategy was to use validated

![Image](https://example.com/fig3.png)

Fig. 3. Funnel plots for CV markers of challenge/threat. Black dots = studies included in the meta-analysis. White dots = studies “filled” based on the trim-and-fill method estimation.

Table 2

| HR | PEP | Performance type | Measurement method | Research design |
|----|-----|------------------|--------------------|----------------|
|    |     |                  |                    | Q (1) | p.h  | Q (1) | p.h  | Q (1) | p.h  | Q (1) | p.h  |
| CO | 0.06 | 0.80             | 0.72               | 0.40  | 1.11 | 0.29  |       |       |       | 1.89 | 0.17 |
| TPR| 0.19 | 0.66             | 0.76               | 0.38  | 0.85 | 0.31  |       |       |       | 4.53 | 0.03 |
| CTI| 0.18 | 0.67             | 0.30               | 0.58  | 0.03 | 0.86  |       |       |       | 9.04 | 0.001|

CO = cardiac output, TPR = total peripheral resistance, CTI = Challenge-Threat Index, HR = heart rate, PEP = pre-ejection period. Performance type coded 0 = behavioral, 1 = cognitive. Measurement methods coded as 0 = discrete, 1 = continuous. Research design coded as 0 = non-experimental, 1 = experimental; p.h = probability of Q given no true differences between effect sizes.
physiological markers of challenge and threat with the same methods of measurement. Second, all investigations of challenge and threat have been tested with samples of young adults. Thus, the generalizability of our findings is limited to this age group. More studies are needed to address the robustness of the biopsychosocial model across the life-span because cardiovascular efficiency changes with age (Mitchell et al., 2004). Consequently, little is known about whether or not the physiological benefits of challenge also facilitate behavioral outcomes in older age.

In conclusion, we have provided new evidence for the significance of CO, TPR, and, to a lesser extent, CTI in predicting successful performance. These findings are an essential contribution to the literature because they document the significance of this evidence and they also present its limitations. Our understanding of challenge and threat would benefit from further studies on more diverse populations (e.g., seniors), in addition to a less selective publication process that would allow dissemination of psychophysiological findings, whether they rejected the null hypotheses or not.

Declarations of interest
None.

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