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Contactless Real-Time Heart Rate Predicts the Performance of Elite Athletes: Evidence From Tokyo 2020 Olympic Archery Competition

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Abstract
It is widely recognized that psychological stress impairs performance for elite athletes, yet direct evidence is scarce when it comes to high-stakes competition because measuring real-time psychological stress without interference is often challenging. Contactless real-time heart rate—a technology-enabled biomarker of stress—was measured and broadcast on TV during the 2020 Tokyo Olympics archery competition for the first time in sports. Here we examined whether the real-time heart rate of 122 adult archers predicted their performance in this unique setting. We found that higher heart rate—which indicates an increase in psychological stress—is associated with lower scores, correlation coefficient $r(2096) = -.076$, $p < .001$, and the observation is robust after we controlled for fixed effects at the individual and match level. Our results provide the first direct evidence in support of the detrimental effect of psychological stress measured by a real-time biomarker in a high-stakes competitive setting.

Keywords
psychological stress, performance, heart rate, sport, open data

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Psychological stress is ubiquitous in modern societies and has gained increasing attention from scientists, policymakers, and the public. Although a moderate amount of psychological stress can be beneficial for tackling difficult tasks, high psychological stress has been found to be detrimental for performance and well-being (Baumeister, 1984; Beilock, 2010; Yerkes & Dodson, 1908). For example, in sports, athletes often exhibit an acute and significant performance decrement in competitive and presumably stressful situations (Mesagno & Beckmann, 2017). In high-stakes competitive settings, when individuals are randomly assigned to conditions with different psychological stress levels, those in the high-stress condition often perform worse than those in the low-stress condition (Apesteguia & Palacios-Huerta, 2010; Ariely et al., 2009; Dohmen, 2008; Gneezy et al., 2011). These studies provide important support for the detrimental effect of psychological stress in competitive environments, but real-time stress when individuals perform the tasks is yet to be directly measured.

Recent technological advances enable researchers to use wearable and noninvasive devices to measure real-time heartbeats as a biomarker for stress (Harford et al., 2019; Pham et al., 2021). Heart rate, the rate of cardiac beats per minute, increases when individuals are under pressure (Chrousos, 2009; Vrijkotte et al., 2000). In the "fight or flight" response to stress, adrenaline is released, inducing an accelerated heart rate. This in turn enables individuals to be better prepared to meet the challenge of stressful situations (Chrousos, 2009). The heart's response to stress parallels other stress biomarkers, such as salivary cortisol (Kirschbaum et al., 1993), and

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is increasingly used as a noninvasive biomarker to measure stress response (Ortega et al., 2018; Peper et al., 1994). Yet real-time heart rate has not been measured to assess the effect of psychological stress for elite athletes in high-stakes competitions, because it is often impractical and obtrusive to use wearable devices in these settings.

We took advantage of a unique setting—the 2020 Tokyo Olympics archery competition—in which heart rate prior to each shot was measured and broadcast on TV during matches throughout the entire competition. Heart rate was measured in a contactless manner using high-frame-rate cameras placed 12 meters from the shooting line to infer heart rate in real time on the basis of the athlete's skin reflectance (Harford et al., 2019). Camera-based heart rate has been proven to be highly accurate. In a meta-analysis based on 26 studies, camera-based heart rate demonstrated a high correlation of 0.962 with heart rate measured by standard medical devices, such as pulse oximeter and electrocardiogram instruments (Pham et al., 2021). The 2020 Tokyo Olympics archery competition was the first time in sports history that this technology was used to monitor elite athletes in a high-stakes competition. Among other benefits, the technology allowed the TV audience to experience the psychological stress felt by the archers. The great majority of archers (122 out of 128) agreed to have their camera-based heart rate measured and broadcast on TV so that sample selection bias, if any, is small. Building on existing studies regarding the detrimental effect of psychological stress on performance and heart rate as a stress biomarker, here we used the broadcast data to test the hypothesis that higher heart rate is correlated with lower scores in this high-stakes competitive setting.

Statement of Relevance

Although it has been widely documented that high psychological stress can be detrimental for performance, it remains a question whether elite athletes would also be subject to the influence of psychological stress. This question is of great interest, but it is often challenging to measure real-time stress of elite athletes in a high-stakes competition. Recent technological advances have enabled cameras to measure real-time heart rate in a contactless manner. This technology was used during the archery competition in the 2020 Tokyo Olympics: Heart rate prior to each shot was measured and broadcast on TV. In this unique setting, we found that high real-time heart rate was associated with poor performance. Our finding supports the notion that psychological stress among elite athletes has detrimental effects. This has important policy implications for performance under psychological stress.

Method

Participants

Our study consisted of 128 athletes in archery at the 2020 Tokyo Olympics. The 2020 Olympics were postponed to 2021 because of the COVID-19 pandemic, and the archery competition took place in Yumenoshima Park from July 23 to 31, 2021. Heart rate was measured using a camera-based method. High-frame-rate cameras were placed 12 meters from the shooting line to track changes in skin reflectance, from which heart rate can be inferred. Heart rate information was broadcast on TV during all matches of the elimination rounds, although it was not displayed on screens in the archery field to minimize the potential influence on the archers.

In the 2020 Tokyo Olympic Games, there were five types of archery competitions: within-gender individual (men and women), within-gender team (men and women), and mixed-gender team. Heart rate information was collected and broadcast on TV for the two within-gender individual competitions. A total of 128 archers—64 men and 64 women—competed in the within-gender individual competitions. When the organizer asked for permission to measure and broadcast heart rate before the game, 122 out of the total 128 archers agreed.

Procedure

In the Tokyo 2020 Olympic archery competition, archers stood in front of a target that was 70 meters distant and shot arrows. If the arrow hit the center of the target, they got a perfect score of 10 points; otherwise, they got scores ranging from 9 points to 0 points, depending on the arrow's distance from the center of the target.

The archery individual events proceeded in several stages. In the initial ranking-round match, each archer shot 72 arrows and was ranked by total scores within gender. These ranks determined their matched competitors in the forthcoming 1/32 elimination matches: The archer ranked first was matched with the archer ranked 64th, the archer ranked second was matched with the archer ranked 63rd, and so on. The ranking-round match was not broadcast on TV, so we did not have heart-rate data for this stage of the competition.

In each match of the elimination rounds, two archers competed. There were about five sets, each consisting of three arrows shot alternately by each of the two archers. Each archer was given 20 s to shoot. The archer who got the higher total points from the three arrows earned 2 points for the set; the other archer earned no points for the set. If both archers earned the same score, each earned one set point. The archer with the higher total set-point score won the match—that is, if one archer won the first three sets, that archer won the match outright, and the match ended. If there was a tie after five sets, more arrows would be shot to decide the winner. Winners of the round-of-32 elimination matches would compete in the round-of-16 elimination matches, and if these archers continued to win, they would advance to the quarter-final, semi-final, and final matches. To sum up, in each individual event (men and women), 64 archers competed in 64 matches; in each match, two archers competed in five sets of three arrows each.

Shooting order in the elimination rounds was determined as follows. The higher-ranked athlete decided the order of shooting in the first set. In the remaining sets, the athlete with the lower set-point score shot first; when there was a tie, the athlete who shot first in the first set would still shoot first.

Results

Our research team watched the videos broadcast on TV for all matches of the within-gender individual competitions and recorded the following information: heart rate, arrow speed, order of shot, and timing of shot. The videos displayed one or more real-time heart-rate data points within the given 20 s for each shot. We recorded the available heart-rate information. Of the 3,290 arrow shots, 2,247 had one or more heart-rate data points broadcast on TV. The missing data were due to technical problems caused by inclement weather during five matches in the 1/32 eliminations. For those arrow shots for which the archer's heart rate was broadcast on TV, 30.8% had one data point, 39.6% had two data points, 12.8% had three, and 16.8% had four or more. In the main results, we used the mean of the available heart-rate data points before each shot as the independent variable to represent heart rate. We also collected detailed match information and the archer's individual information from the official website of the Tokyo Olympics (https://olympics.com/tokyo-2020/olympic-games/en/results/archery/olympic-schedule-and-results.html). Given that the study used an existing data set, we did not seek approval of the Institutional Review Board (IRB).

Statistical analysis

We used regression models to study the relationship between heart rate and performance using several specifications. The first model, reported in column 1 in the main tables, takes the following simple form:

$$Score_{i,m,j} = \alpha + \beta\, Heart_{i,m,j} + \varepsilon_{i,m,j}. \tag{1}$$

Here $Score_{i,m,j}$ and $Heart_{i,m,j}$ are scores and heart rate, respectively, for archer i's arrow j in match m. In all the regression models, we clustered the standard errors at the match level to account for the possible correlations within the same match.

In column 2 in the main tables, we added more control variables, including individual-specific variables and arrow-specific variables:

$$Score_{i,m,j} = \alpha + \beta\, Heart_{i,m,j} + \gamma I_i + \lambda M_{m,j} + \varepsilon_{i,m,j}. \tag{2}$$

Here I_i represents the individual-specific variables including age, gender, world ranking, and round ranking. $M_{m,j}$ are arrow-specific variables that represent the stage (or round) of the match, set of the match, arrow number, shot order, and countdown time for the arrow. (We used integers 1 to 6 to represent the round of 32, the round of 16, the quarterfinal round, the semifinal round, and the final round.)

In column 3 in the main tables, we considered the match-archer fixed effect:

$$Score_{i,m,j} = \alpha + \beta\, Heart_{i,m,j} + R_{i,m} + \varepsilon_{i,m,j}. \tag{3}$$

Here $R_{i,m}$ is the match-archer fixed effect to control for all time-invariant factors at match level and archer level including age, gender, and ranking as well as the stage of the match, weather during the match, and more. This helped us focus on the impact of the variation in heart rate (within the same match, for the same archer) on the archers' performance and reduce potential omitted-variable bias at the match and archer level.

In column 4 in the main tables, we added more arrow-specific variables to the regression:

$$Score_{i,m,j} = \alpha + \beta Heart_{i,m,j} + R_{i,m} + \lambda N_{m,j} + \varepsilon_{i,m,j}. \tag{4}$$

Here $R_{i,m}$ represents the match-archer fixed effect. $N_{m,j}$ are arrow-specific variables representing set number, arrow number, shot order, and countdown time for the arrow.

The 128 archers competed in 128 archery matches, and each archer competed with another archer in five sets of three shots each. The score had a mean of 8.81 points (standard deviation = 1.11), and it was the dependent variable of interest. Of the shots, 28.57% had a perfect score of 10 points, 39.70% a score of 9 points, and 31.73% a score of 8 points or below. On the basis of the televised broadcast, we recorded the

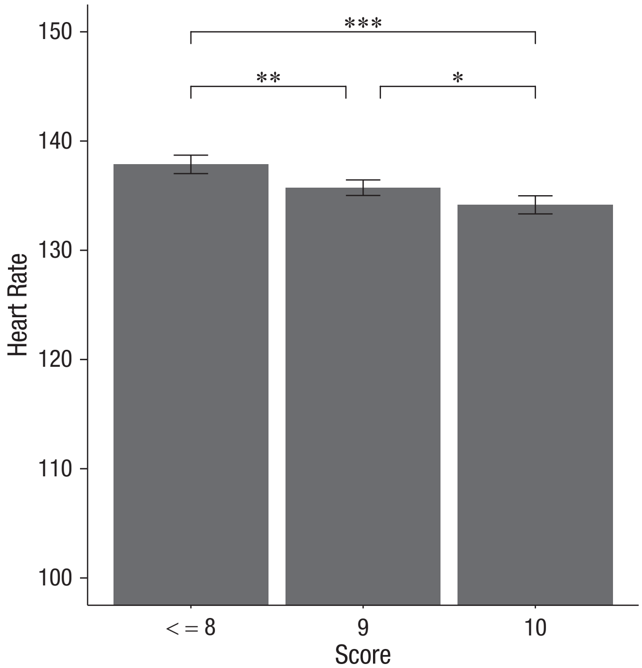

Fig. 1. Heart rate and score. *Heart rate* is the mean of all the available data points before the shot in beats per minute (bpm). We show the mean and the standard error of heart rate for each of the three groups. The one-sided p value of testing difference between groups using a t test is indicated by asterisks. Error bars represent standard errors. *p = .10. **p = .05. ***p = .01.

available heart-rate data points and computed the mean heart rate before each shot to index psychological stress as the main independent variable of interest. Because of the intense competition, heart rate varied from 61 to 190 beats per minute (bpm), with a mean of 135.9 bpm (SD = 20.9). More details are provided in Figure S1 and Table S1 in the Supplemental Material available online.

Heart rate and performance

We first examined the relationship between the archers' mean heart rate before shooting—a direct measure of stress response—and the corresponding scores for each arrow. Figure 1 displays the mean heart rate for three groups: shots with scores of 8 points or below, shots with a median score of 9 points, and shots with a perfect score of 10 points. It showed a clear negative association: Shots completed by archers with higher heart rates had lower scores (Cuzick's test for trend = −3.07, p = .002).

We further tested the above relationship using regression analysis (see the Method section for details) and reported the results in Table 1. Without controlling for any other variables, we found that the coefficient of heart rate was −0.004 (p = .013; see column 1): That is, one more beat each minute led to a 0.004-point decrease in the scores. This means that a 1 standard deviation increase in heart rate (SD = 20.90) led to a 0.075 standard deviation decrease in the scores (SD = 1.11). In column 2, we found that the coefficient of heart rate slightly decreased to −0.003 (p = .012) after we controlled for individual-specific variables and arrow-specific variables.

To further control for unobserved characteristics of the archers and the matches, we added the match-archer fixed effect in column 3. Inclusion of the match-archer fixed effect enabled us to focus on the relationship between scores and heart rate within one match for the same archer. We found that the coefficient of heart rate increased to −0.008 (p = .005). In column 4, we further added the arrow-specific variables to the match-archer fixed-effects regression. We found that the coefficient remained the same (−0.008; p = .003). Of these control variables, scores were higher for shots in the later stages, later sets, or later arrows, as well as for first shots and shots with more time left.

In terms of effect size, the correlation coefficient between heart rate and scores was $r(2096) = -0.076, p < .001$. Alternatively, using the specification in column 4, we found that R^2 was increased by 0.6%, from 24.1% to 24.7%, when heart rate was added to the regression analysis with all the controlled variables. The effect is small in part because elite athletes are trained to cope with psychological stress in their careers.

Instead of mean heart rate prior to shooting, we also used an alternative measure—the heart rate immediately prior to shooting—and found that the above results were robust across the same regression specifications (see Table S2 in the Supplemental Material). Moreover, our results were also robust after controlling for the standard deviation of heart rate (Table S3). Overall, we found a robust negative association between heart rate and scores across the regression specifications.

Heterogeneous effect

We further examined whether the observed effects of heart rate differed across archer-level variables, including gender, age, world ranking, and ranking-round standing, as well as match-level variables, such as stages of the game and the number of the set within matches. We included each of these variables and their interaction terms with heart rate and examined whether the interaction terms were significant (Table 2). We found a significant effect of the stages of the game: In column 5 of Table 2, the interaction term between heart rate and the dummy variable for the matches in the first

Table 1. Heart Rate and Score

Dependent variable	Score	Score	Score	Score
Heart rate	–0.004**	–0.003**	–0.008***	–0.008***
	(0.002)	(0.001)	(0.003)	(0.003)
Age		0.003		
		(0.005)		
Female		–0.263***		
		(0.056)		
World ranking		–0.001*		
		(0.000)		
Ranking-round rank		–0.008***		
		(0.002)		
Stage		0.123***		
		(0.018)		
Set		0.051***		0.055***
		(0.017)		(0.019)
Arrow		0.039		0.043
		(0.029)		(0.031)
Countdown time		0.018*		0.031**
		(0.009)		(0.013)
Shot order		–0.113**		0.152**
		(0.049)		(0.064)
Constant	9.375***	8.999***	9.878***	9.349***
	(0.205)	(0.273)	(0.359)	(0.378)
Match archer fixed effect	No	No	Yes	Yes
Observations	2,096	2,047	2,096	2,096
R^2	0.006	0.097	0.238	0.247

Note: *Score* is the athlete's score on one shot. *Heart rate* is the mean of all the available heart-rate data points in beats per minute (bpm) before the shot. *Age* is the age of the athlete. *Female* is a dummy variable (1 = female, 0 = male). *World ranking* is the world ranking of the athlete when attending the Olympics. *Ranking-round rank* is the ranking of the athlete in the ranking-round match. *Stage* is an indicator for the different stages of the archery competition—1 means 1/32 elimination, 2 means 1/16 elimination, and so on. *Set* is an indicator for different sets of a match ranging from 1 to 6. *Arrow* is an indicator of which arrow was shot in a set (ranging from 1 to 3). *Countdown* is the countdown time before the shot. *Shot order* is a dummy variable (1 = shot first, 0 = shot later). The *match archer* fixed effect is a set of dummy variables for different matches and different athletes. Standard errors in parentheses are clustered at the match level.
*p = .10. **p = significant at .05. ***p = significant at .01.

stage was negative and significant (p = .025). This suggested that the negative association between heart rate and performance was stronger in the later stages of the match, perhaps because the matches in those stages were more competitive and stressful. A marginally significant effect of rank in the ranking round was observed: The negative association between heart rate and performance was stronger for those with lower ranks. No other interaction terms were statistically significant. These observations were robust when we split the whole sample into two subsamples based on these variables—for example, males and females, above and below median age, above and below median rankings, or first-stage matches and the rest of the matches (see Tables S4 to S9).

Inverted-U curve

The relationship between stress and performance is likely to be an inverted-U curve, as suggested by the Yerkes–Dodson law—that is, performance increases as stress level increases until it hits a threshold, and then it decreases as stress level increases beyond the threshold. Our setting was likely to be highly stressful, so we were interested in testing this possibility. Plotting the mean score for each 10% quantile of the heart rate (Fig. S2), we observed an inverted-U shape between heart rate and performance. We further conducted some regression analyses with a quadratic term of the heart rate (Table S10). We found that the coefficient of the quadratic term was significantly negative without

Table 2. Heterogeneous Effect of Heart Rate on Score

	Gender	Age	World Ranking	Ranking round	Stage	Set
Dependent variable	Score	Score	Score	Score	Score	Score
Heart rate	–0.008***	–0.004	–0.009**	–0.016***	–0.003	–0.008***
	(0.003)	(0.004)	(0.004)	(0.006)	(0.003)	(0.003)
Heart Rate × Female	–0.001					
	(0.005)					
Heart Rate × Age		–0.008				
		(0.006)				
Heart Rate × World Ranking			0.001			
			(0.005)			
Heart Rate × Ranking Round				0.011*		
				(0.006)		
Heart Rate × Stage					–0.012**	
					(0.005)	
Heart Rate × Set						–0.000
						(0.001)
Set	0.055***	0.056***	0.055***	0.055***	0.050**	0.055
	(0.019)	(0.019)	(0.020)	(0.019)	(0.019)	(0.034)
Arrow	0.043	0.043	0.041	0.048	0.042	0.043
	(0.032)	(0.031)	(0.032)	(0.032)	(0.032)	(0.031)
Countdown time	0.031**	0.031**	0.029**	0.032**	0.030**	0.031**
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Shot order	0.152**	0.150**	0.159**	0.146**	0.159**	0.152**
	(0.064)	(0.063)	(0.065)	(0.065)	(0.063)	(0.064)
Constant	9.346***	9.251***	9.362***	9.458***	9.387***	9.350***
	(0.376)	(0.390)	(0.380)	(0.391)	(0.368)	(0.381)
Match archer fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,096	2,096	2,063	2,096	2,080	2,096
R^2	0.247	0.248	0.248	0.249	0.251	0.247

Note: *Score* is the athlete's score on one shot. *Heart rate* is the mean of all the available heart-rate data points before the shot in beats per minute (bpm). *Age* is the age of the athlete. *Female* is a dummy variable (1 = female, 0 = male). Heart Rate × Female is the interaction term between heart rate and female. Heart Rate × Age is the interaction term between heart rate and a dummy variable (1 = the athlete's age is ≥ 27, 0 otherwise). Heart Rate × World Ranking (Heart Rate × Ranking Round) is the interaction term between heart rate and a dummy variable (1 = the athlete's world ranking [ranking-round ranking] is higher than or equals to 56 [32], 0 = otherwise). Heart Rate × Stage is the interaction term between heart rate and a dummy variable (1 = athlete's match is 1/32 elimination, 0 = otherwise). Heart Rate × Set is the interaction term between heart rate and a dummy variable of set (1 = the first two sets in the match, 0 = otherwise). *Set* is an indicator for different sets of a match (ranging from 1–6). The arrow is an indicator of different arrow shots in a set (ranging from 1–3). Countdown is the countdown time of the shot. Shot order is a dummy variable (1 = a given archer shot first, 0 = the archer shot later). *Match archer fixed effect* is a set of dummy variables for different matches and different athletes. Standard errors in parentheses are clustered at the match level.
*p = .10. **p = .05. ***p = .01.

controls and became insignificant after we controlled for the match-archer fixed effect, suggesting the likelihood that there was individual heterogeneity regarding the relationship between heart rate and performance. Hence, we further separated the analyses by different type of athletes, including gender, age, and ranking (Table S11), and we found that the inverted-U-shape relationship was observed only in the subsample of low world-ranking or low ranking-round-ranking athletes. Overall, these results provided partial support for the inverted-U-curve relationship between stress and performance among the low-ranking athletes but, intriguingly, not among the high-ranking athletes.

Correlates of heart rate

Although our analyses suggested that the stress biomarker was correlated with performance, we wondered whether the correlation was specific to performance or shooting behavior in general. To answer this question, we examined the correlations between arrow speed and countdown time. Arrow speed was weakly correlated with scores, $r(2165) = .1921$, $p < .001$, but it was not significantly correlated with heart rate (Table S12). Another important measure was countdown time for each shot: If less countdown time was left, this indicated that the archer had taken more time to prepare for the shot. Although countdown time was not correlated with scores, $r(2096) = -0.0122, p = .5766$, we found that the coefficient of heart rate was negative and significant ($p < .001$) when we controlled for the match and archer fixed effect (Table S13). This suggested that when athletes had higher heart rates, they took more time to shoot. Nevertheless, the observed negative correlation between heart rate and scores was robust regardless of whether or not we controlled for countdown time (see the regression results in Table 1).

Given that heart rate was associated with scores, we sought to establish its determinants. We ran regression analyses with heart rate as the dependent variable and archer and match-related variables as independent variables (Table S14). We found that archers in the later sets, having less countdown time, and shooting second tended to have higher heart rates. This was consistent with the psychological-stress interpretation: Athletes who left less time to shoot had higher heart rates because of the time pressure, and archers who shot second had higher heart rates because they were stressed by the performance of the first competitor. Although these factors may underpin the stress responses indexed by heart rate, our previous results in Table 1 show that a high heart rate was associated with low scores after controlling for these factors.

Moreover, given the detrimental effect of stress, archers may have chosen to shoot when their heart rates were lower. We compared their heart rates before shooting with their previous heart rates within the given 20 s of each shot, and we found that 37.9% had a lower heart rate prior to the shot, 38.7% had higher heart rates prior to the shot, and the remaining 23.4% had the same heart rate. We further added to the regression analyses a dummy variable that indexed whether heart rate prior to the shot was slower than the previous heart rate (Table S15). We found that coefficients of this dummy variable were statistically insignificant and the coefficients for heart rate remained significant. Overall, this result suggests that archers on average did not choose to time their shots for when their heart rates were lower, and this timing decision did not contribute to differences in performance.

Dynamic effect

We also explored the dynamic structure of the competition and examined whether the score at the previous shot affected performance. When we added this explanatory variable into our main regression models (see Table S16 in the Supplemental Material), we found that the coefficient and statistical significance of the score at the previous shot was negative and significant after the inclusion of the match-archer fixed effect. In addition, the coefficient and statistical significance of heart rate remained the same. Similar results were found when we used the Arellano-Bond model to mitigate the endogeneity problem (see Table S17).

Finally, we examined another dynamic effect—whether leading versus lagging in a competition affected performance (Apesteguia & Palacios-Huerta, 2010; González-Díaz & Palacios-Huerta, 2016). To examine this effect, we plotted the score relative to the difference of the previous total set points between the athlete and his or her opponent (see Fig. S3). We observed that athletes tended to have lower scores when lagging and have slightly higher scores when leading. We further evaluated the relationship in regression analysis with the previous total-points difference as the main explanatory variable (see Table S18). Note that we did not include an athlete-match fixed effect to avoid the concern of regression to the mean. We found that the coefficient of the previous total-points difference was significant without any control variables ($p < .01$) but became insignificant ($p = .116$) after controlling for demographic and match-specific variables. Similar results were observed when we used dummy variables to indicate leading and lagging for the previous set points and when we did a subsample analysis for those in the first-stage matches and the later-stage matches (Table S19). Overall, the above results suggest that lagging in set points had a negative impact on performance, but the effect became smaller and insignificant after we controlled for other variables.

Discussion

Our observed detrimental effect of psychological stress was consistent with the anecdotal evidence of some archers in the 2020 Tokyo Olympics. In the 1/16 eliminations, Deepika Kumari, the world champion in the World Cup, had a heart rate of 175 in the fifth set and later commented, "Obviously, I'm nervous. The pressure at the Olympics is at a different level as you put in years of effort to win a medal here" ("Winning Olympic medal," 2021). Top seed Kim Je-deok had an increase in heart rate from 120 bpm in the first set to 170 bpm in the fifth set and eventually lost the match. He later said, "I felt a bit of pressure, and was nervous," and acknowledged that this hurt his performance (Park, 2021). Elite athletes usually receive training to manage psychological stress (Hanton et al., 2009), but our results suggest that they continue to be subject to the influence of psychological stress.

A growing line of research has attempted to assess gender differences in performance in response to psychological stress in competitive settings (Gneezy et al., 2003). Interestingly, the results were mixed. Some studies found little evidence that women perform worse than men in more competitive settings for teachers and professional tennis players (Lavy, 2013; Paserman, 2007), whereas some studies showed that men appear to outperform women when competitive pressure was higher in academic settings (Azmat et al., 2016; Cai et al., 2019; Ors et al., 2013). Because the Olympics archery competition was within-gender, we cannot directly examine a potential gender gap in performance. Nevertheless, we observed that real-time psychological stress had a similar detrimental effect on performance for both males and females.

Our study contributes to the broad literature incorporating neurobiological and physiological data into studies of human behavior. The technological advances in recent decades have enabled researchers to obtain rich information about genes, neural activities, and hormonal responses that are useful in investigating a wide range of behavioral traits. These studies substantially broaden the scope of both empirical evidence and theoretical modeling, giving rise to the interdisciplinary field of neuroeconomics (Camerer et al., 2005; Glimcher et al., 2009). Nevertheless, some have argued that evidence from neurobiological and physiological data have no direct implications for the assumptions or the conclusions of the revealed-preference-based economic models (Gul & Pesendorfer, 2008; Rubinstein, 2008). Here we showed that heart-rate data, a physiological measure, can be useful in understanding human behavior because it provides a way to directly test the well-known hypothesis regarding the detrimental effect of psychological stress.

Stress response, often characterized as a *fight-or-flight response*, activates the two main physiological systems: the fast action of the sympathetic adrenal-medullary axis and the relatively slow action of the hypothalamic-pituitary-adrenal axis. The hypothalamus alerts the pituitary gland to send a signal to the adrenal gland. The adrenal gland in turn releases stress hormones, including cortisol and adrenaline, which cause increases in blood sugar, heart rate, and blood pressure. This process enables a quick release of energy into the bloodstream to prepare the body for stressful situations. Cortisol, as the primary stress hormone, has been found to be important in competitions (Apicella et al., 2011; Buser et al., 2017; Cahlíková et al., 2020; Zhong et al., 2018). Studies have also shown that sex hormones—for example, testosterone and progesterone—may also play an important role in competition-related behavior (Apicella et al., 2011; Pearson & Schipper, 2013; Wozniak et al., 2014). Our study added to this literature by showing that heart rate, which indexes stress in elite athletes, was correlated with their performance in a high-stakes competition.

Sports provide competitive and high-stake settings with high-quality data for social scientists to test various theories and hypotheses (Palacios-Huerta, 2014). Given the well-defined rules and clear incentive for performance, data obtained from sporting events allow researchers to achieve better external validity regarding the role of stress in competition compared with laboratory studies. Studies with sports data have proved to be highly fruitful (Apesteguia & Palacios-Huerta, 2010; Medvec et al., 1995; Palacios-Huerta, 2003; Pope & Schweitzer, 2011; Walker & Wooders, 2001). In a study of psychological stress in sports (Apesteguia & Palacios-Huerta, 2010), it was observed that first movers in penalty shootouts in soccer had a 21-percentage-point advantage in terms of winning probabilities compared with second movers, which supports the detrimental effect of psychological stress on performance. We also found correlational evidence that the athletes who shot first had lower heart rates (see Table S14), which supported the link between shot order and psychological stress. Our study contributed to this important literature by providing evidence regarding the impact of psychological stress on performance using contactless real-time heart rate in the archery competition.

Our study has several limitations, related to data availability and the specific setting involved. First, the observed link between psychological stress and performance was correlational rather than causal. Nevertheless, our analyses controlled for the fixed effects at both archer and match level; our findings were not due to differences between archers and different matches. Second, while psychological stress most likely underpinned our observations, we cannot rule out other mechanisms. For example, apart from stress, high heart rate may decrease precision in shooting. Nevertheless, research showed that scores were not affected by lowering heart rate through the administration of beta-adrenergic receptor blockers to inhibit the binding process of noradrenaline (Ergen et al., 2021). Moreover, we observed that heart rate changed in response to stress-related factors such as countdown time and shooting order, which supports the idea of heart rate as a stress biomarker associated with performance.

Last, we would like to point out that our results also have some potential limitations in terms of generalizability. Our findings are based on one type of sport in the specific setting of Olympic competition. It would be of great interest to examine different types of elite athletes across different competitive settings with a larger sample size. We envisage that such studies will be increasingly feasible with the technological advances in measuring real-time heart rate. We hope that future researchers will be able to examine these issues further. Readers should interpret our results with this potential limitation in mind.

Conclusion

We made use of the unique setting of the 2020 Tokyo Olympics archery competition in which real-time heart rate was measured and broadcast on TV for the first time in sports history. We found that heart rate prior to each shot was negatively correlated with scores. This is the first evidence in support of the detrimental effect of real-time psychological stress—as indexed by heart rate—on the performance of elite athletes in the competitive setting of Olympic archery, and the technology used has the advantage of being contactless and available in real time.

Camera-based heart rate as a biomarker is a highly accessible tool for researchers seeking to conduct laboratory and field experiments to examine the role of psychological stress. Moreover, since the COVID-19 pandemic has drastically limited face-to-face interactions, this method could become increasingly important in diverse settings, ranging from sports and business to mental health and medicine. In this regard, our study can be viewed as a proof of concept by showing that contactless real-time heart rates captured psychological stress and was associated with the performance of elites in a highly competitive environment.

Transparency

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Yunfeng Lu: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Visualization; Writing – original draft; Writing – review & editing.
Songfa Zhong: Conceptualization; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing.
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All data have been made publicly available via Open Science Framework and can be accessed at https://osf.io/32jsy/. The analysis plans for the study were not preregistered. This article has received the badge for Open Data. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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Supplemental Material

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