Live sports spectating promotes oxytocin dynamics and heart rate synchrony in casual fans

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Abstract

Regular live sports spectating improves mental health through reduced loneliness, yet the neurobiological responses underlying these benefits during a single session remain unclear. Here, we tested whether live spectating elicits socio-physiological responses, oxytocin release and heart rate (HR) synchrony depending on baseline oxytocin levels. We measured HR and hormonal responses in 60 casual fans during live university basketball games. In the high-baseline oxytocin group (n = 30), oxytocin levels remained elevated throughout the games, whereas in the low-baseline group (n = 30), oxytocin increased to levels comparable to the high group, without increases in cortisol. Oxytocin promoted a sense of unity mediated by subjective enjoyment. HR synchrony during and after the games increased in both groups, associated with oxytocin levels. Finally, HR synchrony predicted psychological flow and team loyalty, mediated by unity. Our findings demonstrate that a single spectating session enhances social bonding through oxytocin dynamics linked to physiological synchrony.

Introduction

From ancient rituals to modern arenas, humans have consistently gathered and formed social bonds through shared emotional experiences, whether in the context of religion, warfare, or communal festivals[1–5]. Such collective engagement is rooted in the fundamentally social nature of human beings[6], who rely on cooperation and shared belief systems to construct and maintain complex societies[7]. Sports serve as a peaceful and institutionalised continuation of these collective practices, providing structured settings for group identity formation, emotional contagion, and social cohesion[8]. In the digital era, emerging cultural domains such as esports expand these functions by enabling synchronous engagement and community formation across physical and virtual environments[9]. Following the global social disruptions caused by the COVID-19 pandemic, both traditional and digital forms of sports have been increasingly recognised as inclusive and embodied avenues for fostering social affiliation and psychological resilience[10].

Building on this sociocultural foundation, while the benefits of active sports participation are widely recognised, the act of sports spectating is increasingly acknowledged as more than a passive pastime[11–14]. Earlier studies reported potential adverse effects of spectating, such as alcohol-related aggression and increased cardiovascular risk during emotionally intense matches[15–18]. However, a growing body of recent research suggests that attending sports events or watching broadcasts can enhance subjective well-being[19,20], reduce psychological distress[21], and alleviate loneliness[22]. Reaching hundreds of millions of individuals across age groups, cultures, and geographic regions, this form of sports engagement is now understood to contribute meaningfully to individual well-being and social connection, beyond the well-established benefits of active sports participation.

One factor thought to contribute to the beneficial effects of sports spectating is the influence of physiological responses during individual viewing experiences. For example, merely observing another person running elevates the observer's heart rate (HR)[23], suggesting that humans experience physiological arousal in response to others' actions, even in the absence of any physical effort. In sports spectating, HR similarly increases during games, and this response is modulated by the outcome of the match[24]. Furthermore, watching a victory is associated with increased testosterone levels, a hormone thought to enhance motivational drive and vigour[25,26], whereas observing a defeat is linked to elevated cortisol levels, which indicate a stress-related response[27,28]. A recent neuroimaging study showed that sports spectating activates the dopaminergic reward system in the brain[29,30]. These findings suggest that sports viewing induces specific physiological changes in the spectator, which in turn influence psychological states such as arousal, stress, and enjoyment. However, the physiological mechanisms that underlie the social connection elicited by spectating remain largely unknown.

Beyond individual-level physiological responses, bodily processes that arise through interpersonal interaction during shared experiences, such as sports spectating, also warrant attention within the domain of socio-physiology[31]. One of the main neuroendocrine candidates involved in these responses is oxytocin, a peptide hormone that plays a central role in regulating social bonding and affiliative behaviours in mammals[32]. Physical interactions, including skin-to-skin contact between mothers and infants[33], hugging[34], or sexual behaviour[35], activate oxytocin secretion, depending on baseline oxytocin levels[36–38]. Martial arts practice, which involves structured physical contact, also increases salivary oxytocin levels[39], and oxytocin reactivity during martial arts practice differs depending on individual's baseline levels[40]. In addition, mutual eye contact with humans[41] or with companion animals[42] stimulate oxytocin release without direct physical contact. When oxytocin dominates over cortisol, this hormonal profile promotes empathy, emotional synchrony, and a sense of social closeness[43,44]. Therefore, sports spectating, even with little or no physical contact, could lead to oxytocin-dominant hormonal profiles.

In addition to facilitating emotional bonding, oxytocin plays a role in coordinating physiological states between individuals, known as physiological synchrony[45]. This phenomenon refers to the temporal alignment or convergence of physiological signals such as HR, skin conductance, and pupil diameter between individuals, typically observed during social interactions involving shared emotional or attentional engagement[45]. Although the dynamics of oxytocin in sports spectating remain unclear, few study to date has examined physiological synchrony in spectating and reported that HR synchrony among spectators was significantly greater during in-person attendance at a live basketball game compared to on-screen viewing[46]. Since oxytocin and physiological synchrony are closely related and mutually reinforcing[47,48], sports spectating could promote synchronisation of physiological states associated with oxytocin.

We here aimed to test the hypothesis that sports spectating promotes oxytocin release and HR synchrony depending on baseline oxytocin levels. We specifically tested this hypothesis in Japanese university basketball home games, a naturalistic setting characterized by modest crowds and predominantly casual fans, to evaluate whether socio-physiological benefits emerge outside large professional arenas and, critically, whether they do so without stress-related costs often reported among highly devoted fans[28]

Results

To examine whether watching sports promotes oxytocin release and HR synchrony in relation to baseline oxytocin levels, 60 participants watched a university basketball game (Fig. 1A). The two games analyzed were both part of "TSUKUBA LIVE!", the home event series of the

University of Tsukuba. Unlike professional sports events, these matches attracted modest audiences primarily composed of students and local residents, reflecting a casual rather than a devoted fan base. Saliva samples to measure hormonal activity and questionnaire data were collected before the game, at halftime, and immediately after the game, while HR was continuously recorded throughout spectating (Fig. 1B, C). Participants were classified into the low-OT (n = 30, mean age 22.9 years, 11 females) and high-OT (n = 30, mean age 22.2 years, 10 females) groups based on baseline oxytocin concentrations measured before the game (median = 27.51 pg/ml; Fig. S1). Baseline oxytocin levels were significantly higher in the high group than in the low group ($t = 9.65$, $p < 0.01$, $d = 2.46$). No significant group differences were observed in sex, age, body composition, resting HR, or physical activity, indicating that the classification was determined solely by baseline oxytocin levels.

Sports spectating promotes oxytocin dynamics depending on baseline levels.

We examined whether sports spectating elicits distinct hormonal responses depending on baseline oxytocin levels. Oxytocin concentrations significantly increased in the low-OT group, reaching levels comparable to the high-OT group by the end of the game ($F_{2, 116} = 11.67$, $p < 0.0001$, $\eta_p^2 = 0.16$; Fig. 2A). In contrast, the high-OT group maintained elevated oxytocin throughout the game without significant temporal changes ($F_{1, 58} = 29.06$, $p < 0.0001$, $\eta_p^2 = 0.33$; Fig. 2A). Cortisol concentrations decreased across both groups ($F_{1.8, 102.7} = 3.32$, $p = 0.045$, $\eta_p^2 = 0.05$; Fig. 2B), resulting in a consistent increase in the oxytocin-to-cortisol ratio throughout spectating ($F_{1.7, 95.7} = 14.50$, $p < 0.0001$, $\eta_p^2 = 0.20$; Fig. 2C). Together, these findings indicate that sports spectating modulates hormonal dynamics depending on baseline oxytocin levels but ultimately shifts both groups toward an oxytocin-dominant hormonal balance.

High oxytocin promotes unity through enhanced enjoyment.

Next, we examined how oxytocin during watching influences spectators' subjective experiences. Questionnaires assessed a sense of unity (IOS scale[49]) and enjoyment (VAS). Unity with home players ($F_{1.48, 84.41} = 24.39$, $p < 0.0001$, $\eta_p^2 = 0.30$; Fig. 3A) and home team fans ($F_{1.82, 104.10} = 12.36$, $p < 0.0001$, $\eta_p^2 = 0.17$; Fig. 3B) increased across watching regardless of baseline oxytocin levels. Enjoyment also increased in both groups ($F_{1.79, 101.70} = 22.18$, $p < 0.0001$, $\eta_p^2 = 0.28$; Fig. 3C), but the effect was more pronounced in the high-OT group ($F_{1, 57} = 6.59$, $p = 0.012$, $\eta_p^2 = 0.10$).

As shown in Fig. 3D, oxytocin concentrations were significantly associated with enjoyment ($r = 0.21$, $p = 0.006$), unity for players ($r = 0.24$, $p = 0.001$) and fans ($r = 0.16$, $p = 0.037$). Separate mediation analyses further demonstrated that oxytocin enhanced unity with players through enjoyment ($z = 2.74$, $p = 0.006$, 95% CI [0.005, 0.023]; Fig. 3E) and similarly

enhanced unity with fans through enjoyment ($z = 2.61$, $p = 0.009$, 95% CI [0.004, 0.022]; Fig. 3E). These findings indicate that oxytocin amplifies enjoyment during spectating, which in turn promotes social bonding among spectators.

Sports spectating enhances HR synchrony via oxytocin dynamics rather than baseline levels.

We examined whether sports spectating increases HR synchrony and whether this synchrony is associated with oxytocin. HR followed similar trajectories in both groups, with mean ($F_{2.57, 146.20} = 84.37$, $p < 0.0001$, $\eta_p^2 = 0.59$; Fig. 4B) and maximum ($F_{3.14, 182.30} = 170.90$, $p < 0.0001$, $\eta_p^2 = 0.74$; Fig. 4C) levels significantly elevated compared to pre-game values. Cross-correlation analyses revealed that HR synchrony increased in both groups during the first and second half ($F_{2.97, 169.50} = 28.19$, $p < 0.0001$, $\eta_p^2 = 0.33$; Fig. 4D). Furthermore, time lags of HR dynamics shortened during and after the game, indicating enhanced synchrony ($F_{3.03, 172.60} = 31.39$, $p < 0.0001$, $\eta_p^2 = 0.36$; Fig. 4E). In addition, oxytocin levels were positively associated with HR synchrony ($r = 0.15$, $p = 0.041$). Notably, this association was more pronounced in the low-OT group, where oxytocin was significantly related to both CCF ($r = 0.28$, $p = 0.009$) and time lag values ($r = -0.26$, $p = 0.014$) (Supplementary Fig. 1B, D). These findings suggest that sports spectating promotes HR synchrony among spectators regardless of baseline oxytocin levels, with oxytocin dynamics contributing to the processes supporting this synchrony. Importantly, these effects were observed during collegiate games with casual audiences, indicating that bonding mechanisms based on HR synchrony generalize beyond the highly fused fan groups typical of professional settings.

HR synchrony enhances the spectating experience through a sense of unity.

Finally, we examined how physiological synchrony relates to social bonding and the overall spectating experience. To capture the functional role of synchrony, HR data were reclassified into “in-game” periods (when players were actively playing) and “out-of-game” periods (including inter-quarter intervals, halftime and post-game). In-game (Fig. 5A), lag values were significantly negatively correlated with unity toward the home team players ($r = -0.45$, $p < 0.01$) and flow state ($r = -0.41$, $p < 0.01$), indicating that stronger moment-to-moment alignment (i.e., shorter lag) was associated with enhanced affiliative and immersive responses. Out of game (Fig. 5B), ΔCCF (from pre) values were positively correlated with unity toward home spectators ($r = 0.39$, $p < 0.05$) and intention to revisit the event ($r = 0.27$, $p < 0.05$), suggesting that physiological synchrony outside play reflected broader social bonding among spectators.

To test potential mediating roles of social bonding, we conducted mediation analyses. In-game, HR synchrony (time lag) influenced flow state via unity with players as a mediator (z

= -3.32, $p < 0.001$, 95% CI [-0.69, -0.19]; Fig. 5C). Out of game, ΔCCF influenced the intention to revisit via unity with fans ($z = 2.08$, $p < 0.05$, 95% CI [0.50, 4.81]; Fig. 5D). These results suggest that physiological synchrony not only reflects but also facilitates the formation of social bonds that shape meaningful psychological experiences during live spectating.

Discussion

We aimed to test the hypothesis that live sports spectating promotes oxytocin release and HR synchrony in relation to baseline oxytocin levels. To this end, we examined the effect of baseline oxytocin levels by comparing low-OT and high-OT groups. During spectating, oxytocin increased in the low-OT group but remained elevated in the high-OT group. Oxytocin further promoted unity with players and fans mediated by enjoyment. HR synchrony was enhanced across groups regardless of baseline oxytocin levels and was positively associated with oxytocin dynamics by spectating. Moreover, HR synchrony fostered flow state and a loyalty through unity with players and spectators. Collectively, our findings suggest that watching live sports facilitates oxytocin dynamics in associated with HR synchrony, thereby strengthening social connections among spectators.

Why does watching sports promote oxytocin dynamics? One of the key findings of this study is that watching sports promotes oxytocin dynamics depending on baseline levels (Fig. 2A). Previous research has demonstrated that oxytocin release is facilitated by social experiences such as eye contact and storytelling[42,50]. Our results indicate that similar mechanisms may also be engaged during watching sports. Elements such as indirect eye contact mediated through players, the embodied performance conveyed by athletes, and the unscripted dramatic nature of the game share key features with storytelling. The collective enjoyment of these elements, as a fundamental human social practice, may serve as a form of "embodied storytelling" that enhances oxytocin dynamics and provides a basis for strengthening social bonds among spectators.

Mediation analyses further demonstrated that oxytocin fostered unity with players and fellow fans through enhanced enjoyment (Fig. 3E). This mediating relationship may be accounted for by the neural mechanism whereby oxytocin potentiates activity in the brain's reward system. Oxytocin receptors are abundantly expressed in regions central to reward processing, including the ventral tegmental area (VTA) and nucleus accumbens (NAc)[51]. Animal studies have shown that oxytocinergic neurons in the hypothalamic paraventricular nucleus project directly to the VTA, where they enhance dopaminergic signaling via oxytocin receptors[52]. Converging evidence in humans indicates that intranasal oxytocin increases activation of the VTA and NAc when viewing a partner's face[53]. Collectively, these findings

support the notion that oxytocin enhances the valuation of social stimuli through reward-related pathways. While watching sports has long been known to engage the reward system[54], the neural basis of social bonding during collective spectating has remained elusive. Our results suggest that elevated oxytocin during watching sports may amplify reward system activity as a form of social reward, thereby providing a neural mechanism for fostering unity with players and fellow fans.

Beyond its actions on mesolimbic structures underlying the reward system, oxytocin may also influence higher-order regions of the prefrontal cortex. A prominent candidate is the ventromedial prefrontal cortex (vmPFC). The vmPFC receives projections from the VTA and NAc and is well established as a core component of the reward system[55], yet it is also engaged by others' successes and socially salient events, implicating it in vicarious reward processing[56]. Recent evidence further indicates that oxytocin enhances vmPFC activity[57,58]. Thus, the facilitation of oxytocin dynamics during watching sports may strengthen unity with players and fellow fans through modulation of vmPFC function.

Why does watching sports promote HR synchrony irrespective of baseline oxytocin levels?

This study demonstrated that live sports spectating promotes HR synchrony among spectators irrespective of baseline oxytocin levels (Fig. 4D, E). Such synchrony is likely driven by the intense collective arousal elicited during spectating. Shared external stimuli—including the tension of the game, the roar of the crowd, and collective reactions—act as powerful forces that align cardiac dynamics across individuals, transcending individual hormonal baselines. Physiological synchrony has similarly been observed in other collective events such as music concerts and religious rituals, where it is regarded as a physiological substrate of shared group experiences[59,60]. Our findings suggest that watching sports shares this property, functioning like other collective gatherings in fostering synchrony among casual fans.

Another key finding of this study is the observed association between endogenous oxytocin levels and HR synchrony (Fig. 4F). Although both oxytocin release and physiological synchrony are facilitated in collective events and social interactions such as eye contact, their direct coupling has rarely been tested. Previous studies showed that exogenous oxytocin increases physiological linkage in small groups during cooperative tasks, and research in parent–infant dyads links endogenous oxytocin to interactive synchrony[61,62]. However, to our knowledge, no study has directly linked moment-to-moment fluctuations in endogenous oxytocin to physiological synchrony in a large, naturalistic spectator setting. Evidence that intranasal oxytocin enhances synchrony in laboratory cooperation tasks[47] is therefore mechanistically consistent with our field data, yet the present association in live sports extends these insights to ecologically valid group contexts.

These observations carry translational implications. Oxytocin has long been considered a candidate for improving social functioning in autism spectrum disorder (ASD), but a large, multisite NEJM randomized trial found no benefit of intranasal oxytocin over placebo on core social symptoms in children and adolescents[63] Also, method/theory reviews caution that intranasal delivery yields uncertain brain exposure and potential peripheral off-target effects, underscoring safety and efficacy concerns for exogenous administration[64] In contrast, endogenous oxytocin release through engaging, collective experiences may offer a low-burden, inclusive route to support social connectedness. Live sports spectating has been associated with higher well-being and lower loneliness at the population level[22] and ASD research indicates challenges in spontaneous interpersonal synchrony[65,66] suggesting that synchrony-supportive environments could be valuable adjuncts to social habilitation. While causal clinical benefits remain to be established, our data raise the possibility that inclusive spectator contexts might help harness endogenous oxytocin-linked synchrony to scaffold social engagement in populations with social-communication difficulties.

Taken together, our findings suggest a bidirectional relationship between oxytocin and HR synchrony, with the two processes mutually reinforcing, situating sports spectating alongside other collective gatherings as a naturalistic context that both elicits physiological synchrony and tracks with endogenous oxytocin dynamics.

Sports Spectating as Embodied Storytelling: Past, Present, and Future. Throughout human history, collective practices such as religious rituals, warfare, and communal festivals have synchronised emotions and reinforced social bonds; contemporary evidence links such gatherings to shared arousal and physiological synchrony[60,67]. Sports represent a peaceful and institutionalized continuation of these traditions, fostering group identity, emotional contagion, and social cohesion[68]. The present findings contribute to this historical and anthropological context by demonstrating that watching sports functions as a form of embodied storytelling that elicits oxytocin dynamics and HR synchrony, thereby promoting social connections among spectators. In this sense, watching sports is not only entertainment or competition but also an activity with a biological foundation that translates shared bodily experiences into social cohesion.

Against the backdrop of Japanese collegiate sports, these findings carry particular significance. In the United States, collegiate sports exert far-reaching social influence, supported by strong athletic performance, substantial financial resources, and extensive entertainment infrastructures. By contrast, Japanese collegiate sports have not yet achieved comparable popularity or institutional support[69]. Nevertheless, our study revealed that even in the relatively local and small-scale context of Japanese university basketball, spectators synchronised, forged

social bonds, and developed stronger intentions to revisit. These results indicate that the social benefits of spectating are not confined to professional sports on grand stages; rather, they can also emerge from sharing the efforts of familiar individuals. Such effects may constitute a socio-physiological foundation for community building and the promotion of well-being in local societies through sports.

Looking ahead, an important question is how embodied storytelling might evolve to contribute to future societies. While opportunities for spectating and participation through online streaming and public viewing are expanding, the synchrony and unity they afford remain limited[46]. By contrast, in the context of esports, the real-time sharing of bodily signals such as facial expressions and HR—so-called "bio-sharing"—has been shown to enhance the perceived social presence of others[70]. This suggests that embodiment, a universally available human resource, serves as a foundation for creating social connections. Future work should explore how the sharing of embodiment across time and space can be harnessed to promote collective well-being.

Limitations. While our field-based approach ensured ecological validity by capturing real-time physiological dynamics during live sports events, several limitations should be acknowledged. First, the determinants of individual differences in baseline oxytocin levels remain unclear. In this study, participants were categorized based on the median pre-game oxytocin concentration, and we verified that this classification was not attributable to physical characteristics such as body composition, resting HR, or habitual physical activity. Nonetheless, it remains uncertain whether the observed variability reflects other stable individual traits or transient influences, such as recent social interactions. Second, oxytocin was measured in saliva, leaving the dynamics of oxytocin within the central nervous system unresolved. That said, salivary oxytocin tracks peripheral oxytocin to some extent: in mothers, concurrently sampled saliva and plasma concentrations covary across tasks, and a preregistered meta-analysis reports modest central–peripheral coupling that emerges after experimental stimulation rather than at rest[71,72] In humans, plasma oxytocin has been shown to predict cerebrospinal-fluid oxytocin in a lumbar-puncture study[73]., although other reports find no baseline association, underscoring ongoing measurement debate[74] Accordingly, while salivary assays offer a practical window on the oxytocinergic system in the field, inference to brain dynamics remains indirect; future studies should combine validated peripheral sampling with neuroimaging and, where feasible, pharmacological challenges to delineate the neural mechanisms by which sports spectating fosters social bonding[75]. Third, our analyses focused on spectator dyads sharing similar attributes. Whether HR synchrony also occurs between spectators of different demographics, nationalities, or group affiliations remains unknown. Future research should extend these

investigations to diverse spectator pairings and, importantly, to synchrony between spectators and players.

Conclusion

Live sports spectating promotes baseline-dependent oxytocin dynamics that are associated with HR synchrony. These socio-physiological responses foster enjoyment and social connection in casual fans. Importantly, in contrast to reports in highly devoted fans at emotionally intense events, these responses emerge without stress-related hormonal increases. By linking endogenous oxytocin dynamics to physiological synchrony in a naturalistic spectator setting, our study suggests that casual spectating can encourage sustained community engagement and contribute to a more active, healthier, and more socially connected lifestyle.

Materials and Methods

Participants. We recruited 62 participants. Each participant attended one basketball game, either a victory or a defeat. The loss game included 27 participants, and the victory game included 35 participants, balancing the potential influence of game outcome across groups. Two other participants took part but were excluded from all analyses due to insufficient pre-game saliva samples, leaving 60 participants for the final analysis. Based on the median pre-game salivary oxytocin concentration (27.51 pg/ml), participants were classified into a low-OT group (n = 30; 22.9±9.0 years; 11 females) and a high-OT group (n = 30; 22.2±8.6 years; 10 females). We conducted a power analysis with Partial $\eta^2 = 0.036$, referring a previous study on baseline oxytocin levels and video viewing[76]. A power analysis using G-power 3.1 software showed that a total of 60 participants would be sufficient to detect a significant difference between two independent means in a two-sided analysis with 0.05 alpha and 90% power. The inclusion criteria for participation were as follows: age upper 18 years; ability to understand and sign an informed consent form; no current medication for neuropsychiatric, cardiovascular, or metabolic diseases; and the ability to visit the site of the experiment. This study was approved by the Research Ethics Committee of the Institute of Health and Sport Sciences, University of Tsukuba, and was conducted in accordance with the Declaration of Helsinki.

Experimental design. The experimental protocol used in this study is shown in Fig. 1C. This study was conducted with spectators who attended two basketball games. When requesting participation in the experiment, an outline of the experiment and a URL to answer the pre-survey were sent to the participants via e-mail. Before the experiment, the participants were prohibited from consuming alcohol from the day before the experiment until the end of the experiment, consuming caffeine and engaging in strenuous exercise on the day of the

experiment, and from eating 2 hours before the start of the experiment.

On the day of measurement, participants arrived at the stadium approximately one hour before the game started, received an explanation of the experiment again, and signed an informed consent form. Participants wore a HR monitor (Polar Verity Sense; Polar, Finland) and completed baseline saliva sampling (2 mL) for hormone analysis and psychological questionnaires. Subsequently, they watched the basketball game from the assigned seats. Saliva samples and questionnaires were further collected at halftime and immediately after the game.

Pre-experiment questionnaire. To identify participant's demographic variables, we asked them about their physical activity time. Responses were collected using Google Forms. The Japanese version of the International Physical Activity Questionnaire (IPAQ) was used to measure physical activity time. Some participants did not complete all demographic items, resulting in missing data for certain variables. However, their physiological and psychological data were retained for analysis, as data quality met the inclusion criteria.

Physiological measurements. To evaluate the physiological impacts of sports spectating, we measured the HR, salivary oxytocin and cortisol levels. HR was monitored using standalone optical HR sensor that can wear on the arm. Participants wore the HR senser throughout 30min before the game to 15min after the game. HR was sampled at 1Hz. For analysis, the game period was segmented into "In-game" (when players were on the court) and "Out of game" (including inter-quarter intervals, halftime and the 15 minutes following the end of the game).

Salivary oxytocin and cortisol levels were measured as neuroendocrine markers to ascertain the social bonds and stress response associated with sports spectating. Saliva was spit directly into a sample collection tube using a straw. Two milliliters of saliva were collected and stored immediately after collection in a freezer at -80°C. To precipitate mucus, sample tubes were centrifuged at 1500×g for 20 minutes each. The supernatant was collected, and aliquots were stored at −80 °C until assayed. A 1000 μL portion of the saliva sample was concentrated by centrifugal evaporation, and salivary oxytocin concentration was measured using a competitive enzyme-linked immunosorbent assay (ELISA) kit (Oxytocin ELISA Kit, Enzo Life Sciences, USA). Salivary cortisol concentration was measured also using an ELISA kit (Salivary cortisol ELISA kit, Salimetrics, USA). Measurements were performed in duplicate, according to the kit's instructions. Absorbance was determined and the concentrations of cortisol and oxytocin in the samples were calculated with relevant standard curves with a microplate reader (Varioskan LUX Multimode Microplate Reader, Thermo Fisher Scientific, MA). For all measurements, the coefficient of variation (CV) for duplicate samples was below 5%.

HR data analysis. HR synchrony was assessed using cross-correlation function (CCF) analysis. A temporal lag window of ±30 seconds was applied to identify the maximum correlation between HR time series. The resulting lag values were converted to absolute values to represent the degree of temporal alignment irrespective of direction. Because participants were seated in two groups located on opposite sides of the same courtside, visual perspectives of the game could differ and potentially affect synchrony. Therefore, synchrony scores were calculated within each seating group rather than across all participants. For each participant, the average of dyadic CCF values across all within-group pairings was taken as the individual synchrony score. The baseline HR synchrony was defined as the 5-minute period with the lowest within-group CCF.

Psychological questionnaires. Participants were asked about enjoyment while watching the game, using a visual analog scale (VAS). VAS length was 100mm, and words indicating the degree of sensation ("not enjoyable at all" to "very enjoyable") were noted at both ends. Participants were asked to mark the position in the line segment that the best represented the degree of sensation they were currently feeling. The distance from the left end of the line segment to the intersection of the x-mark and line segment was measured and scored as a percentage (%) of the length of the entire line segment. Also, participants were asked to have a flow scale to measure their flow experience while spectating. This scale consists of four items: "forgetting the time", "being completely focused", "losing oneself", and "enjoying oneself". Responses were scored on a seven-point scale ranging from "not at all" (1 point) to "very much" (7 points), the total score of each item was used as the subjective flow state while spectating. In addition, loyalty scale was used to measure intention to revisit (I would like to watch this event again in the future.) Responses were scored on a seven-point scale ranging from "not at all" (1 point) to "very much" (7 points). Inclusion of others in the self-scale (IOS) was used to measure the sense of unity for players and spectators[49]. This scale presents seven overlapping circles, and the closer the circles overlap, the closer the relationship with the subjects. In this study, we asked respondents to answer about their closeness to four different subjects: the home team players, the home team spectators, the away team players, and the away team spectators. VAS and IOS were measured before the game, after 2 quarter (half time), after the game. Flow scale and loyalty scale were measured only after the game.

Statistical analysis. HR synchrony and mediation analyses were conducted in RStudio. All other analyses were performed using GraphPad Prism 10 software. Depending on the data structure, unpaired t-test or two-way ANOVA were used to examine group differences. When a

significant main effect or interaction was detected, Bonferroni's multiple comparison test was applied. If missing values occurred due to incomplete responses or outlier exclusion, a mixed-effects model was used instead of ANOVA. For mixed-effects models, partial η^2 values were calculated from F-statistics and degrees of freedom and reported as approximate indicators of effect size. All data are presented as mean ± standard deviation. The threshold for statistical significance was set at $p < 0.05$.

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Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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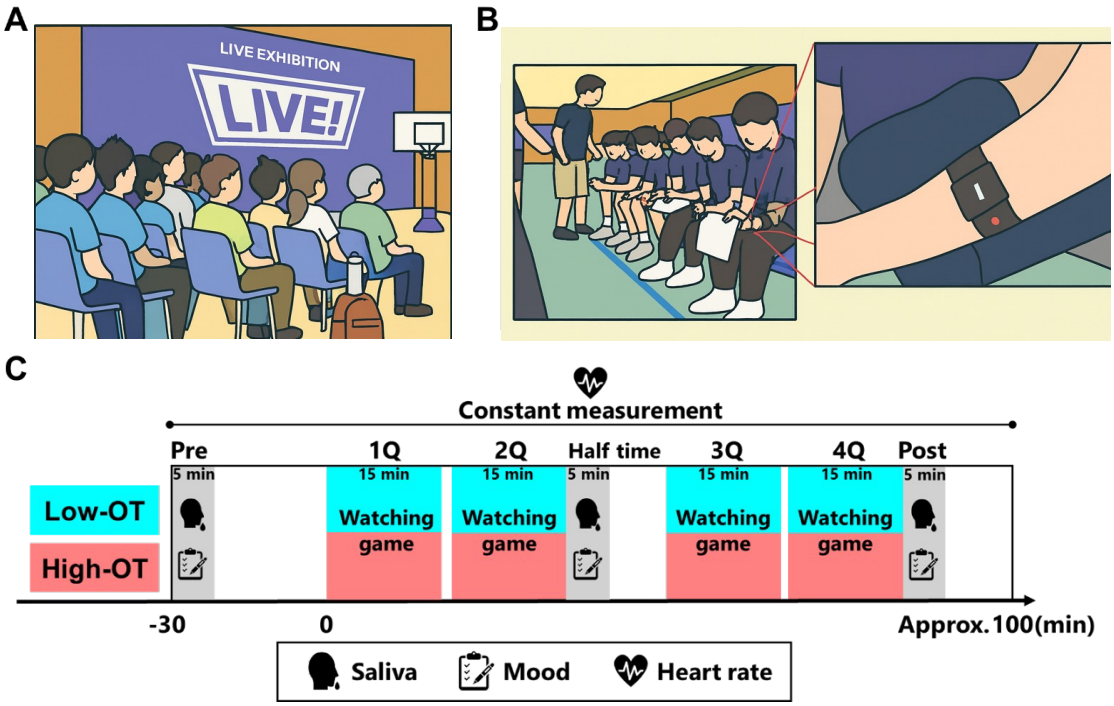

Fig. 1. The experiment protocol

A. An image of the spectating state. **B.** An image of saliva sampling, questionnaire completion, and the HR measurement device. **C.** Overview of the experimental protocol. The participants watch basketball games for 100min. Saliva samples and mood questionnaires were administered before. Each measurement took approximately 5min to complete. The HR was measured during spectating.

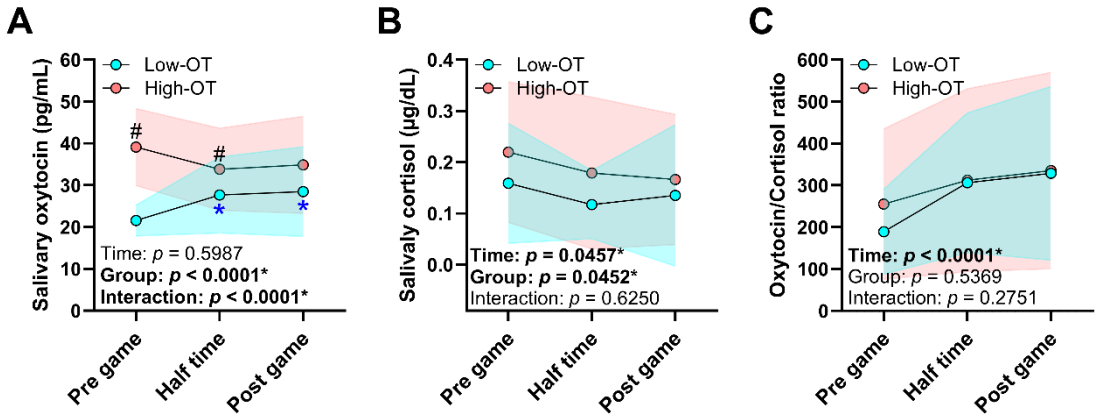

Fig. 2. Watching sports promotes oxytocin dynamics depending on baseline levels.

A. saliva oxytocin levels. **B.** saliva cortisol levels. **C.** oxytocin/cortisol ratio. Data are shown as mean ± standard deviation. SD are shown as blue (Low-OT) and red (High-OT) bands on the graph. Results of mixed effect model are shown in the lower left of each graph. Time: fixed effect of watching time. Group: fixed effect of the group. Interaction: interaction between time and group. *: $p < 0.05$ vs. pre game for both groups; *close proximity to a point on the graph. #: $p < 0.05$ vs. Low-OT. The result representing * and # were calculated using Bonferroni's multiple comparison test.

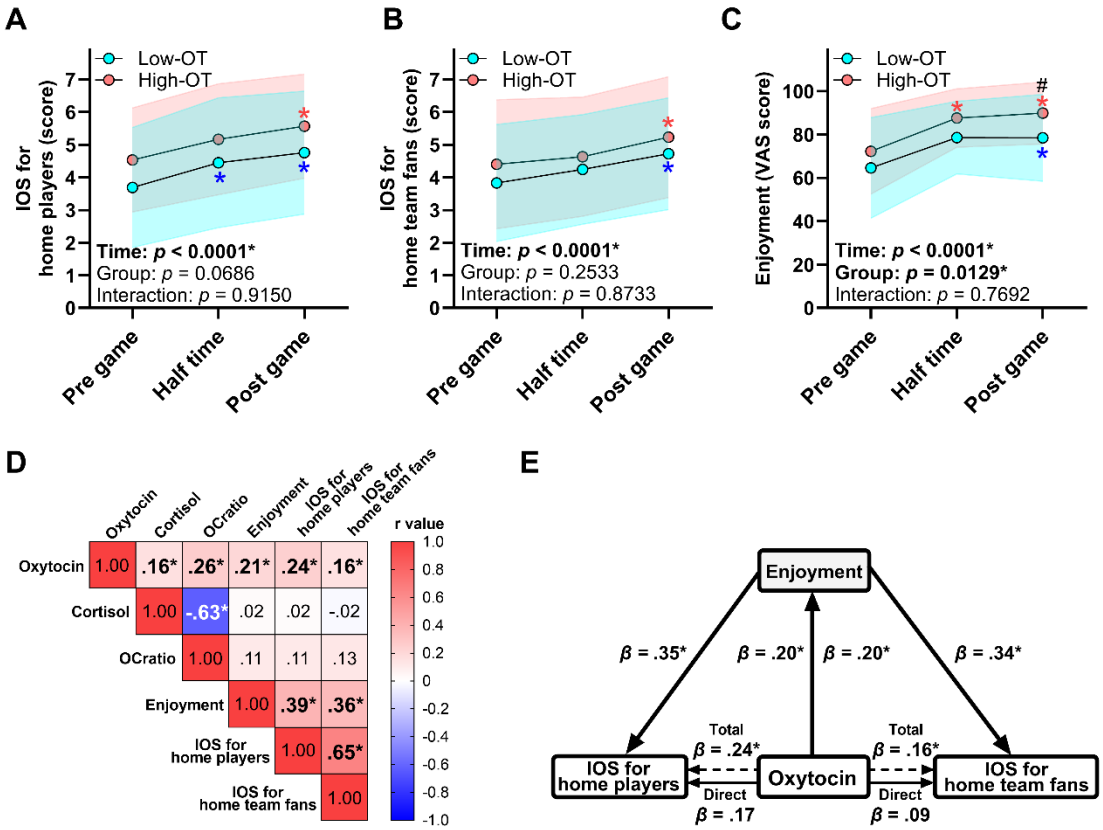

Fig. 3. High oxytocin promotes unity through enhanced enjoyment.

A, B. A sense of unity with home players (A) and home team fans (B). **C**. Enjoyment. Data are shown as mean ± standard deviation. SD are shown as blue (Low-OT) and red (High-OT) bands on the graph. Results of mixed effect model are shown in the lower left of each graph. Time: fixed effect of watching time. Group: fixed effect of the group. Interaction: interaction between time and group. *: $p < 0.05$ vs. pre game for both groups; *close proximity to a point on the graph. #: $p < 0.05$ vs. Low-OT. The result representing * and # were calculated using Bonferroni's multiple comparison test. **D**. correlation matrix summarizing associations between neuroendocrine responses, mood and a sense of unity. **E**. Mediation model showing the associations between oxytocin, enjoyment, and a sense of unity. *: $p < 0.05$.

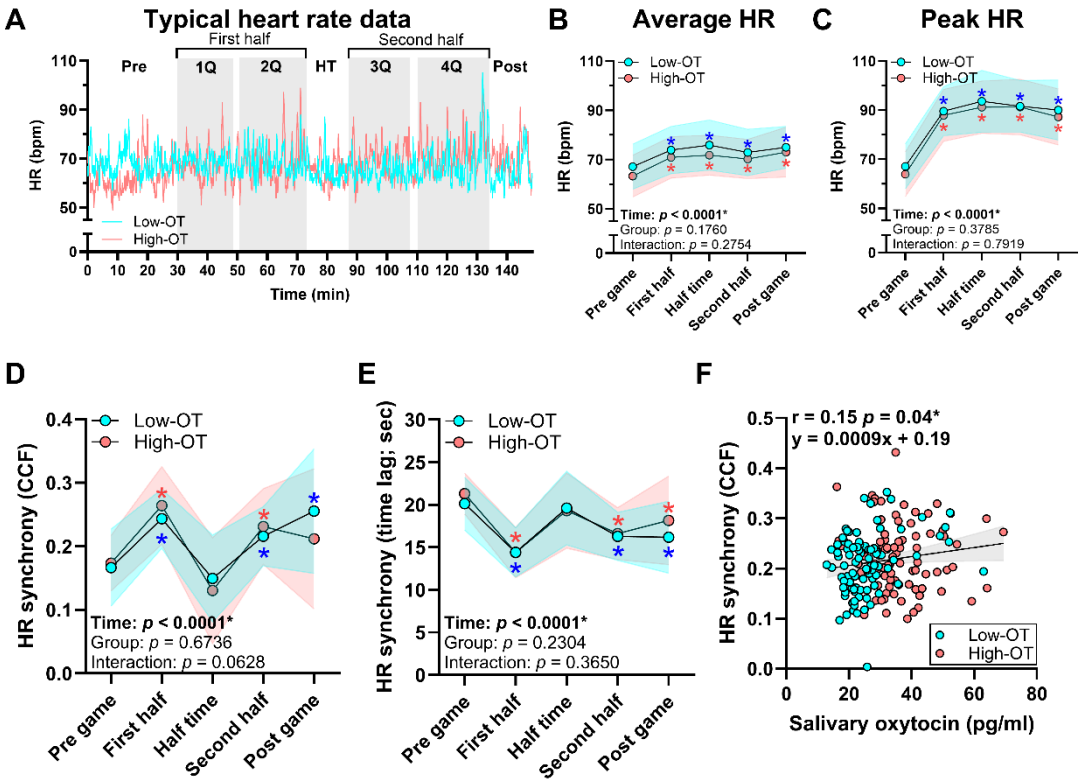

Fig. 4. Watching sports enhances HR synchrony associated with oxytocin.

A. Typical HR data. **B.** Average HR. C. Peak HR. **D.** Similarity of HR dynamics (cross-correlation function; CCF). **E.** Time lag. Data are shown as mean ± standard deviation. SD are shown as blue (Low-OT) and red (High-OT) bands on the graph. Results of mixed effect model are shown in the lower left of each graph. Time: fixed effect of watching time. Group: fixed effect of the group. Interaction: interaction between time and group. *: $p < 0.05$ vs. pre game for both groups; *close proximity to a point on the graph. **F**. Correlation between oxytocin and HR synchrony. The Pearson's product-rate correlation coefficient and the results of the single regression analysis are shown in the upper-left corner of each graph. The computed regression line and 95% confidence intervals are shown as bands on the graph. *: $p < 0.05$.

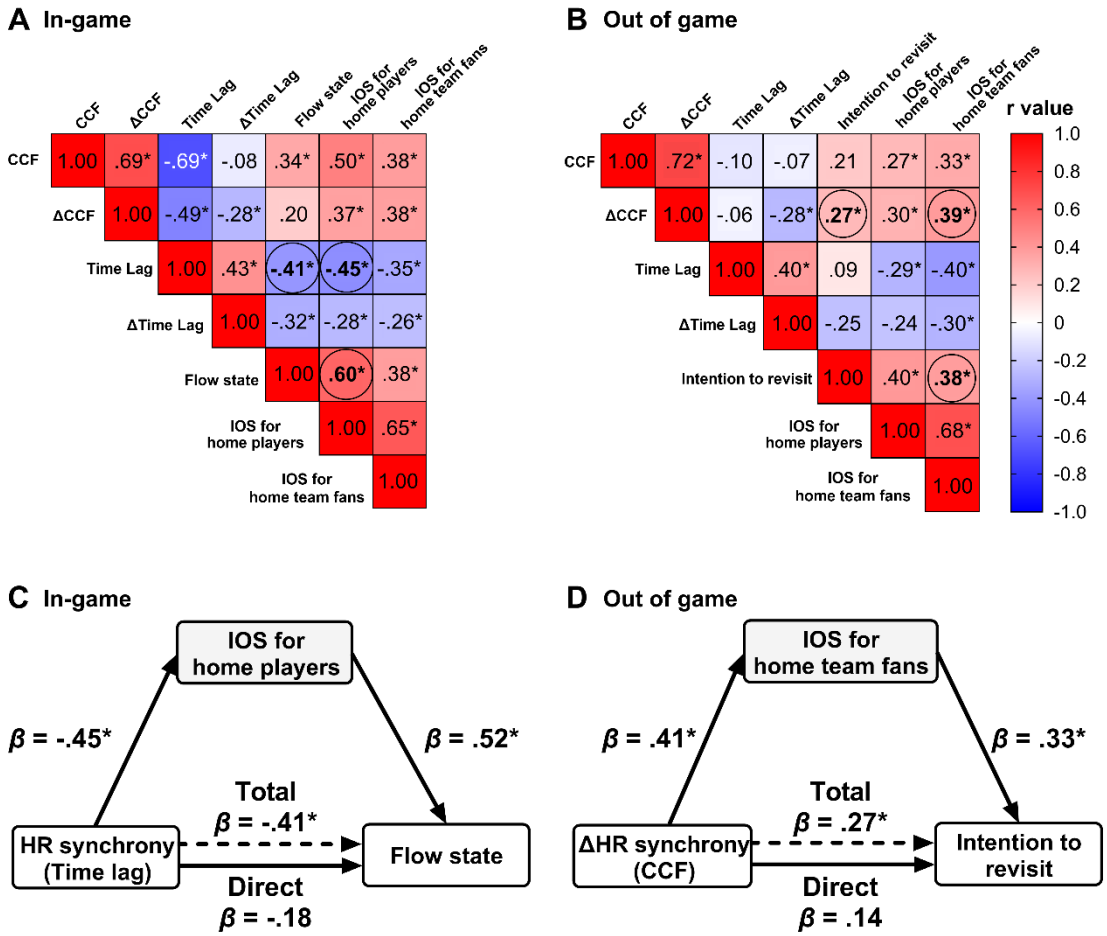

Fig. 5. HR synchrony enhances the spectating experience through a sense of unity. **A.** Correlation matrix between measurements related in-game. **B.** Correlation matrix between measurements related to out of game. **C.** Mediation model of in-game. **D.** Mediation model in out of game. The significance of the correlation analysis is indicated at the top-right of correlation coefficient. * $p < 0.05$.

741 **Table S1. Participants' characteristics**

	Low-OT (n = 30)		High-OT (n = 30)		*p*	*d*
Median oxytocin (pg/ml)	27.5					
Pre oxytocin level (pg/ml)	21.6	± 3.7	39.1	± 9.2*	<0.01	2.46
Age (years)	22.9	± 9.0	22.2	± 8.6	0.77	0.07
Gender (n, Male/Female)	19	/ 11	20	/ 10		
Height (cm)	168.6	± 7.4	172.3	± 9.8	0.11	0.42
Body weight (kg)	65.3	± 8.8	68.6	± 15.8	0.34	0.25
BMI (kg/m^2)	22.9	± 3.3	23.2	± 1.2	0.71	0.11
Resting HR (bpm)	67.1	± 9.4	63.2	± 8.5	0.10	0.43
Vigorous-intensity activity (min/day)	80.7	± 80.8	87.3	± 82.6	0.76	0.08
Moderate-intensity activity (min/day)	20.4	± 39.7	16.8	± 18.9	0.66	0.11
Walking time (min/day)	28.1	± 40.3	24.1	± 29.6	0.67	0.11
Exercise time (min/day)	70.5	± 83.3	70.0	± 67.7	0.97	<0.01
Sitting time (min/day)	284.5	± 160.9	348.6	± 226.6	0.23	0.32
Cheering for home team (score)	6.2	± 0.9	6.6	± 0.5	0.10	0.43

742 Values are presented as mean ± SD.

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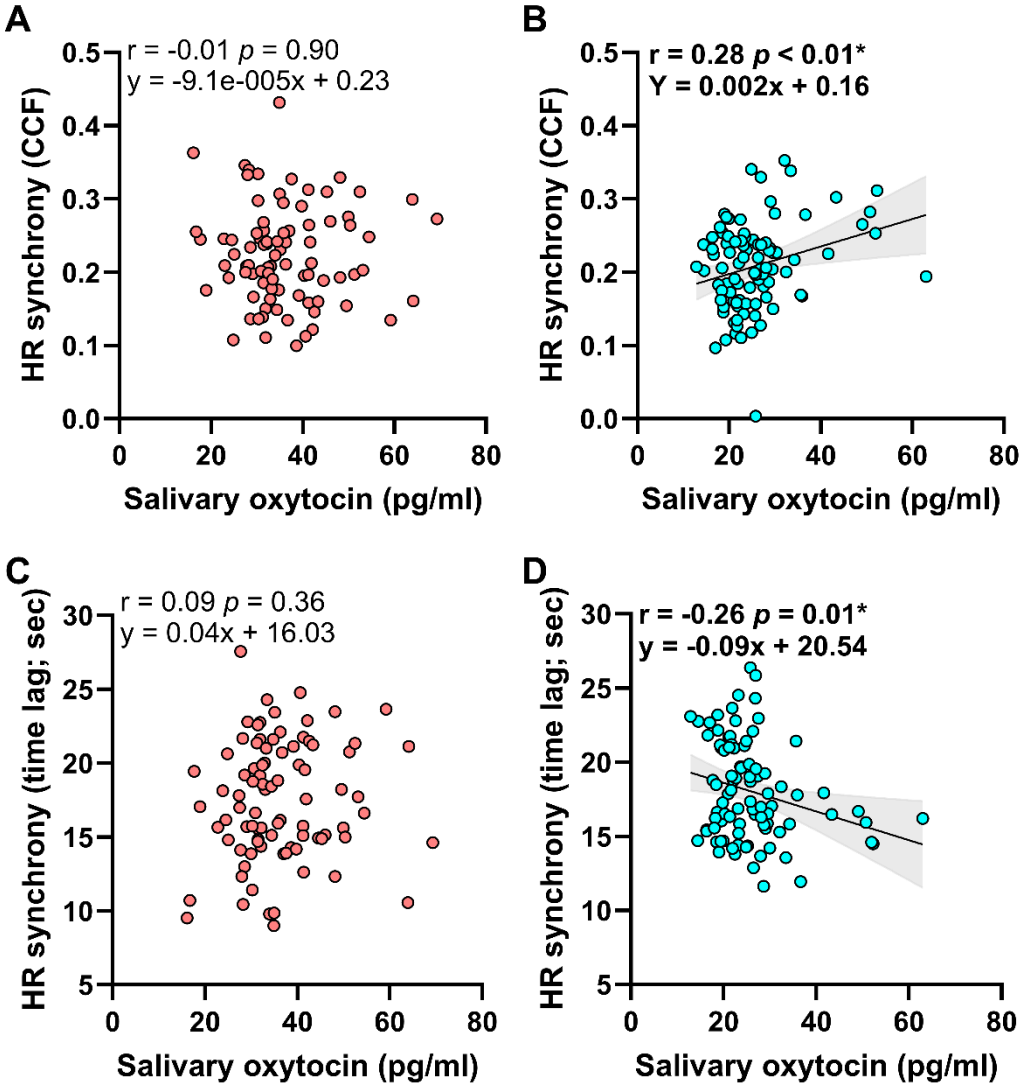

Fig. S1. Stronger relationship between HR synchrony and oxytocin in the Low-OT group. **A, B.** Correlation between oxytocin and HR synchrony (CCF) in High-OT group (A), and Low-OT group (B). **C, D**. Correlation between oxytocin and HR synchrony (time lag) in High-OT group (C), and Low-OT group (D). The Pearson's product-rate correlation coefficient and the results of the single regression analysis are shown in the upper-left corner of each graph. The computed regression line and 95% confidence intervals are shown as bands on the graph. *: $p < 0.05$.